UNIVERSITY OF HELSINKI
FACULTY OF AGRICULTURE AND FORESTRY

High Capacity Transport vehicles in long distance transport of forest energy wood

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Master's Thesis
University of Helsinki
Master's Program of Forest Sciences
Forest Ecology and Management
May 2020

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Title
High Capacity Transport Vehicles in long distance transport of forest energy wood

Subject
Forest Ecology and Management

Level Master's Thesis	Month and year May 2020	Number of pages 103 + 4 Appendices

Abstract

During the last 100 years, Finnish legislation on the maximum vehicle dimensions and gross weights has been an upward trend. Government's decree 407/2013 increased the maximum gross weight of the vehicles up to 76 tonnes and made possible to apply a permit for a High Capacity Transport (HCT) vehicle.

HCT-vehicles are over 25.25 meters long and over 76 gross weight vehicles which are not classified as special transports. HCT-vehicles are in use in Sweden, Brazil, New-Zealand, Canada, United States, South-Africa, Mexico and in Australia. Research on HCT-vehicles has proven HCT-vehicles to lower transport costs and emissions. HCT-vehicles do not compromise traffic safety, congest the traffic flow or be significantly more unstable than a normal vehicle.

Government's decree 31/2019 increased the maximum length of the vehicles up to 34.5 meters, while the maximum gross weight stayed the same. Thus, increasing the cargo space, but decreasing the maximum payload weight on longer (over 25.25 meters) vehicles. In forestry, where the payload weight is a crucial factor, transportation of different timber assortments with an extra-long vehicle is infeasible.

The study aimed to inspect the possibilities of utilizing HCT-vehicles in long distance transportation of forest energy wood, due to the payload weights being lower, but a requirement of cargo space being higher than the other timber assortments.
The study was conducted as a simulation study. Four different types of HCT-vehicles and one normal 25.25-meter vehicle were simulated. Also, two types of chippers and two different types of forest energy woods were simulated. The simulated HCT-vehicles were: 28-, 30-, 32 and 33-meter long HCT-vehicles, based on pre-existing HCT-vehicles. The normal length vehicle was based on an average vehicle. All of the vehicles maximum gross weight were set to be 76 tonnes. Chippers were simulated as a mobile and as a terminal chipper. Every vehicle had their operating costs calculated.

The forest energy wood was simulated as a delimbed stems and harvest residuals. The scenarios were divided into a normal and a dry scenario, according to the energy woods moisture content. The normal scenario had energy woods moisture content to be 40 % and in the dry scenario 20 %. In both scenarios, energy wood is transported as comminuted and uncomminuted energy wood.

The maneuverability of the simulated vehicles and their potential usage on forest roads were inspected using TrailerWIN-program. HTC- and the normal vehicle were built in the program and taken into Finnish 120-degree maneuverability test. The vehicles were assumed not to have extra turning axles and all the axles were assumed to be lowered.

The results in the normal scenario show when transporting comminuted energy wood, HCT-vehicles are inferior when compared to the normal vehicle. HCT-vehicles are up to 1 € more expensive than the normal vehicle per transported MWh. This is due to vehicles reaching their maximum gross weight limit, before filling up the cargo space. When transporting uncomminuted energy HCT-vehicles are superior, when compared to the normal vehicle. HCT-vehicles are up to 2 € cheaper per MWh transported when compared to the normal vehicle on long distances. This is due to uncomminuted' energy woods lower fill grade, thus filling up the cargo space more efficiently.

When transporting comminuted energy wood under the dry scenario, HCT-vehicles perform better. HCT-vehicles are up to 0.5 € less expensive per transported MWh than the normal vehicle on long transport distances. This is due to drier energy woods lower density; the extra cargo space can be utilized more efficiently. When transporting uncomminuted energy wood, HCT-vehicles outperform the normal vehicle. HCT-vehicles are up to 2 € more efficient than the normal vehicle per transported MWh on long transport long distances.

In the maneuverability test, the 30-meter HCT-vehicle and the normal vehicle can be argued to pass it. Thou the result can be held only as a guideline as if extra-long vehicles can be operated on forest roads. The most important aspect on maneuverability is the construct of the vehicle.

Keywords
High Capacity Transport vehicle, forest energy wood, HCT-vehicle

Where deposited
Helsinki University Library – Helda / E-thesis ethesis.helsinki.fi

Additional information

Tiedekunta	Laitos
Maatalous-metsätieteellinen tiedekunta	Metsätieteiden osasto, metsätieteiden maisteriohjelma

Tekijä/Författare – Author
Harri Ruokojärvi

Työn nimi / Arbetets titel – Title
High Capacity Transport ajoneuvoyhdistelmät metsäenergiapuun kaukokuljetuksessa

Oppiaine
Metsien ekologia ja käyttö

Työn laji	Aika	Sivumäärä
Maisterintutkielma	Toukokuu 2020	103 + 4 liitettä

Tiivistelmä

Suomen ajoneuvojen lainsäädännössä on ollut viimeisen sadan vuoden aikana huomattavissa kasvava kehityssuunta. Valtioneuvoston asetus 407/2013 nosti ajoneuvojen maksimi kokonaismassan 76 tonniin ja mahdollisti poikkeuslupien hakemisen High Capacity Transport (HCT) ajoneuvoille.

HCT-ajoneuvot ovat yli 25.25 metriä pitkiä ja yli 76 tonnin kokonaismassan omaavia ajoneuvoja, joita ei lasketa erikoiskuljetuksiksi. HCT-ajoneuvoja on käytössä Ruotsissa, Uudessa-Seelannissa, Kanadassa, Yhdysvalloissa, Etelä-Afrikassa, Meksikossa ja Australiassa. HCT-ajoneuvojen tutkimus on osoittanut HCT-ajoneuvojen alentavan kuljetuskustannuksia ja päästöjä. HCT-ajoneuvot eivät vaaranna liikenneturvallisuutta, hidasta liikenteen sujuvuutta tai eivät ole merkittävästi epävakaampia kuin normaalit ajoneuvot.

Valtioneuvoston asetus 31/2019 nosti ajoneuvojen maksimipituutta 34.5 metriin, maksimi kokonaismassan pysyessä ennallaan. Tämä asetus lisää kuormatilan kokoa, mutta vähentäen maksimi kuorman massaa pidemmillä (yli 25.25 metrin) ajoneuvoyhdistelmillä. Metsätaloudessa, jossa kuljetuksien kuormien massat ovat suuria, eri pyöreän raakapuun puutavaralajien kuljettaminen erikoispitkillä ajoneuvoyhdistelmillä on haastavaa.

Tutkimuksen tavoitteena oli tarkastella HCT-ajoneuvojen käyttöä ja mahdollisuuksia metsäenergiapuun kaukokuljetuksessa. Metsäenergiapuun ollessa kuorman massan suhteen kevyempi, kehystiheyksien ja kuormatilan täyttöasteen ollessa alhaisempia, mutta kuormatilan koon suhteen vaativampi kuin pyöreä raakapuu. Tutkimus toteutettiin simulaatiotutkimuksena. Neljä erilaista HCT-ajoneuvoa ja yksi 25.25 metrin normaali ajoneuvo mallinnettiin. Myös kaksi erilaista hakkuria ja kaksi erilaista metsäenergiapuu lajia mallinnettiin. Mallinnetut HCT-ajoneuvot olivat 28, 30, 32 ja 32 metriä pitkiä, niiden pohjautuessa jo olemassa oleviin HCT-ajoneuvoihin. Normaali ajoneuvo pohjautuu keskiverto 25.25 metriä pitkään yhdistelmään. Ajoneuvojen maksimi kokonaismassan oletettiin olevan 76 tonnia. Hakkurit mallinnettiin terminaali- ja mobiilihakkurina. Jokaiselle ajoneuvolle määriteltiin tuntikustannukset.

Metsäenergiapuu mallinnettiin pienläpimittaisena karsittuna rankana ja hakkuutähteinä. Mallinnetut skenaariot jaettiin normaaliin ja kuivaan skenaarioon, metsäenergiapuun kosteusprosentin mukaan. Normaalissa skenaariossa metsäenergiapuun kosteusprosentiksi oletettiin 40 % ja kuivassa skenaariossa 20 %. Molemmissa skenaarioissa metsäenergiapuu kaukokuljetus suoritettiin haketettuna ja hakettamattomana.

HCT-ajoneuvojen kääntyvyyttä ja niiden potentiaalista käyttöä metsäautoteillä tarkasteltiin TrailerWIN-ohjelman avulla. HCT-ajoneuvot ja normaali ajoneuvot mallinnettiin TrailerWIN-ohjelmaan ja niiden suoritusta tarkasteltiin 120-asteen käännöstestissä. Ajoneuvojen oletettiin ajavan kaikki akselit alhaalla ja ilman kääntyviä akseleita.

Tulokset normaalista skenaariosta osoittavat HCT-ajoneuvojen olevan huonompi vaihtoehto haketetun metsäenergiapuun kuljetuksessa kuin normaali ajoneuvo. HCT-ajoneuvot ovat kustannuksiltaan jopa 1 € kalliimpia per kuljetettu MWh pitkillä kuljetusmatkoilla, kuin normaaliajoneuvo. Tämä johtuu HCT-ajoneuvojen lisääntyneestä omamassasta, jolloin kaikkea kasvanutta kuormatilaa ei päästä hyödyntämään. Hakettamattoman metsäenergiapuun kuljetuksessa HCT-ajoneuvot ovat parempi vaihtoehto kuin normaali ajoneuvo. HCT-ajoneuvot ovat kustannuksiltaan jopa 2 € halvempia per kuljetettu MWh kuin normaali ajoneuvo pitkillä kuljetusmatkoilla. Tämä johtuu hakettamattoman metsäenergiapuun alhaisemmasta kehystiheydestä ja kuormatilan täyttöasteesta.

Kuivassa skenaariossa HCT-ajoneuvojen suoritus haketetun metsäenergiapuun kuljetuksessa on parempi. HCT-ajoneuvot ovat kustannuksiltaan jopa 0.5 € halvempia per kuljetettu MWh kuin normaaliajoneuvo. Tämä johtuu kuivan metsäenergiapuun alhaisemmasta kehystiheydestä, jolloin lisääntynyttä kuormatilaa voidaan hyödyntää. Hakettamattoman metsäenergiapuun kuljetuksessa HCT-ajoneuvot ovat parempia kuin normaali ajoneuvo. HCT-ajoneuvojen kustannukset ovat jopa 2 € halvempia per kuljetettu MWh kuin normaalilla ajoneuvolla. Tämä on seurausta kuivan metsäenergiapuun alentuneesta kehystiheydestä.

Kääntyvyystestissä, 30 metrin HCT-ajoneuvon ja normaalin ajoneuvon voidaan sanoa läpäisseensä testin. Kääntyvyystestin tuloksia voidaan korkeintaan pitää suuntaa antavina ajoneuvojen käytettävyydestä metsäautoteillä. Kääntyvyyden tärkein aspekti on ajoneuvojen rakenne.

Avainsanat
High Capacity Transport ajoneuvoyhdistelmä, HCT-ajoneuvo, metsäenergiapuu

Muita tietoja

Contents

Preface

This is for the ones in the middle of the global pandemic.

This is for the ones, who do not remember how things were at spring 2020.

This is for the ones, who do not remember how we got through it.

This is for my darling, who endured my stress and rambling.

This is for my family, who stood with me through thick and thin.

This is for my friends, who kept my feet on the ground.

This is for the professors, who guided me through the studies and this process despite the pandemic.

This is for the colleagues, who inspired me.

This is for my classmates, who made my studies unforgettable.

This is for my friends from Erasmus+, who taught me see the world.

This is for the ones who believed in me, when I did not believe in myself.

You guys are trve kvlt!

Harri Ruokojärvi

-Still amazed by big trucks

List of abbreviations

A-double: Combination vehicle, consisting of two trailers, connected by a dolly.

Arrival state: The state of the fuel, when delivered.

Articulated vehicle: A vehicle, which has a permanent joint in its construct.

Basic density: Fuels density, when fuel is assumed to have zero moisture content and no empty spaces.

B-double: combination vehicle, consisting of two trailers, connected by a fifth wheel.

Bogie: A rear-wheel assembly, composed of four wheels on two axles.

Bulk density: Density of the fuel, when fuel is considered to contain moisture and empty space.

Calorific heating value: Fuels released energy, when moisture content is zero (Mj/kg).

Combination vehicle: Vehicles, which consists of tractor and or multiple trailers.

Comminution: Chipping or crushing; breaking the structure of energy wood.

Delimped energy wood: Small diameter energy wood, with branches removed.

Directive: An official instruction.

Dolly: A underpowered trailer, which can be used to connect semi- and full trailers together.

Energy content at arrival state: Fuels energy content when fuels bulk density and moisture content are considered.

Fifth wheel: A coupling between a vehicle used for towing and a trailer on top of the tractor truck.

Fill grade: A relation between cargo space and solid payload content. (%)

Follow up-time: The time spent waiting behind the vehicle to be overtaken, before attempting the overtake.

Full trailer: A trailer having wheels at the front and the back.

Gross weight of the vehicle: Vehicles maximum weight bearing capacity. Includes trucks own weight, fuels, tools and a driver.

Guideline: A general rule.

Harvest residuals: Branches, tops and litter from harvested trees.

HCT-vehicle: High Capacity Transport vehicle. Vehicle which is over 25.25-meter-long and or maximum gross weight of 76-tonnes or more.

Infrastructure: Basic physical or organizational structures, roads, power network, which society requires to work.

Legal framework: Laws which are more specific than constitutional provisions. They lay down general obligations and principles but leave local authorities freedom to act on them.

Lower calorific heating value: Fuels released energy, when vaporization of water is considered. (Mj/kg)

Mass-produce: Production of goods by an automated process.

Memorandum of Understanding: A document describing the broad outlines for the agreement between two parties.

MJ: Megajoules. Unit of energy, 10 000 joules.

Moisture content: Quantity of water contained in the fuel. (%)

Pallet: A flat wooden structure that heavy goods are put on to make can be moved more easily.

Payload: Amount of cargo, which vehicle can carry.

Permit: Officially allow to do something.

Safety time: Time difference between passing of incoming vehicle and overtaking vehicle.

Semi-trailer: A trailer having wheels at the back but supported at the front by a tractor.

Tandem operation: Vehicles driving after one other as a fleet.

Tonne: 1000 kilograms, also known as metric ton.

Triple: A combination vehicle, which consists of two or more trailers.

TWh: Terawatt-hour. Unit of energy. Approximately 3.6*10^9 MJ.

1 Background

1.1 Finnish Heavy vehicle legislative evolution through the 20th century

1.1.1 Introduction on heavy traffic legislation

To gain perceptive on HCT-vehicles we have to take a look on Finnish heavy traffic legislation; regulation and progression through decades, starting early 20th century and ending in second decade of 2000's.

1.1.1 The beginning of the 20th century

At the beginning of the 20th century, the legal framework trucks structure did not exist. Vehicle's type was determined to be a truck when vehicle had been equipped with a pallet and it could be used to transport cargo. The first directive on trucks gross vehicle weight came to be on the year 1922 when new directive set maximum gross vehicle weight at 6 tonnes and obligated tires to be made fully out of rubber when operating on highways, which were limited in quantity and length (Giwed 2016). The term highway meant a road, which is paved with natural stones or with gravel. On the lower unpaved I- and II-road class networks, directive set maximum weights on 4,5 and 3 tonnes (Heikinheimo 2009).

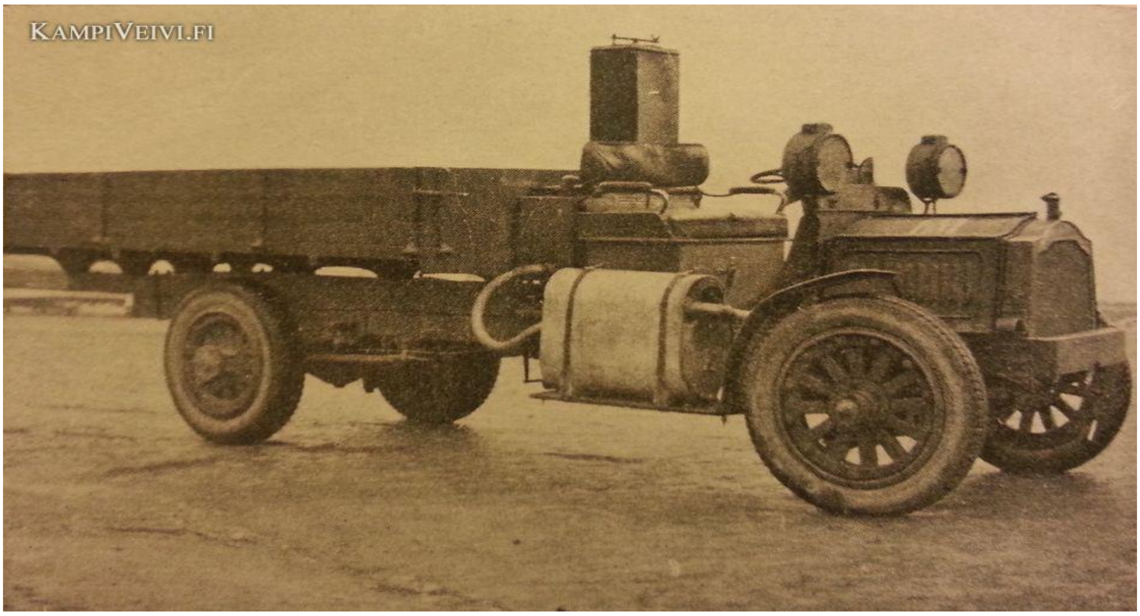

Figure 1. The Finnish army's Pacard truck from 1925. (Source: Kampiveivi.fi)

The next directive changes came in 1926 when maximum gross weight was set to 7.5 tonnes. On 1932 new limit was set to 8.2 tonnes. Going on forward to 1937, the maximum was set to 9 tonnes (Heikinheimo 2009).

The driving forces behind the rapid increase in maximum gross weight of the vehicles were improved construct of vehicles: possibility on equipping multiple axles on a vehicle, improvements of engines power output, air-filled tires and improved road construct methods. (Ahonen 2015; Giwed 2016) Improved design of vehicles and improved infrastructure enabled the next directive to change in 1937 when the maximum gross weight of the vehicles was raised to 9 tonnes (Heikinheimo 2009).

Figure 2. Ford’s truck in Finland 1937. (Source: Finnish National Board of Antiquities -archive)

1.1.2 The mid-20th century

During the 1940’s several manufacturers started to mass-produce new types of equipment for trucks; bins and general cargo constructs, which enabled Finland to witnessed first uses on semi-trailers, which were used for special cargo transports and on vehicle combinations (Ahonen 2015; Giwed 2016). On 1948 new maximum gross weight were raised to 10.1 tonnes (Heikinheimo 2009). After the Second World War and its effects on resources (Ahonen 2015) the next change in legislation came in 1957 when vehicle combinations were recognized by legislative administration and maximum gross weight was set to 24 tonnes. In 1961 the maximum was raised to 30 tonnes (Heikinheimo 2009).

Figure 3. On the back Sisu K-138 (1963) and the front Scania-Vabis L55 (1965). (Source: Iikka Kekko)

1.1.3 Late 20th century

Before 1966 maximum dimensions, the length and width, of the vehicles were not set in the legislation. The only constraints were due to condition of the roads and available technology (Ahonen 2015). The directive changes of 405/1966 increased the maximum gross weight of the vehicles to 32 tonnes and set the maximum dimensions as follows: length for a single-vehicle 11 meters, for a combination vehicle 18 meters and for height 4 meters (Heikinheimo 2009; Giwed 2016).

The next increase in maximum gross weight of the vehicles happened in 1975 when combination vehicles maximum gross weight was increased to 45 tonnes, and the length to 22 meters (Heikinheimo 2009). Maximum gross weight was raised again in 1982 when gross weight was raised to 48 tonnes. (Heikinheimo 2009; Ahonen 2015; Giwed 2016). In 1990, maximum gross weight was increased up to 60 tonnes, during winter, when soil is frozen, while the next change came on 1997, Maximum gross weights were raised to 60 tonnes all year round. Dimensions changed also: maximum length was raised to 25,25 meters and maximum height to 4.2 meters. (Heikinheimo 2009; Ahonen 2015; Giwed 2016).

Figure 4. Volvo FH12 from 1990’s. (Source: Volvo.fi)

1.1.4 21st century

The next major change in the vehicle’s maximum dimensions and weight came in 2013 with government decree 407/2013. It increased the maximum gross weight of the combination vehicles up to 76 tonnes and maximum height of the vehicle to 4.4 meters. (Ahonen 2015; Giwed 2016). In 2019 the maximum length of the combination vehicles was increased further to 34.5 meters with government’s decree 31/2019 (Finlex 2019). I shall examine these governments’ decrees in the following chapters. The changes of maximum gross weight and dimensions from 1922 until 2019 are presented in the figures 5 and 6.

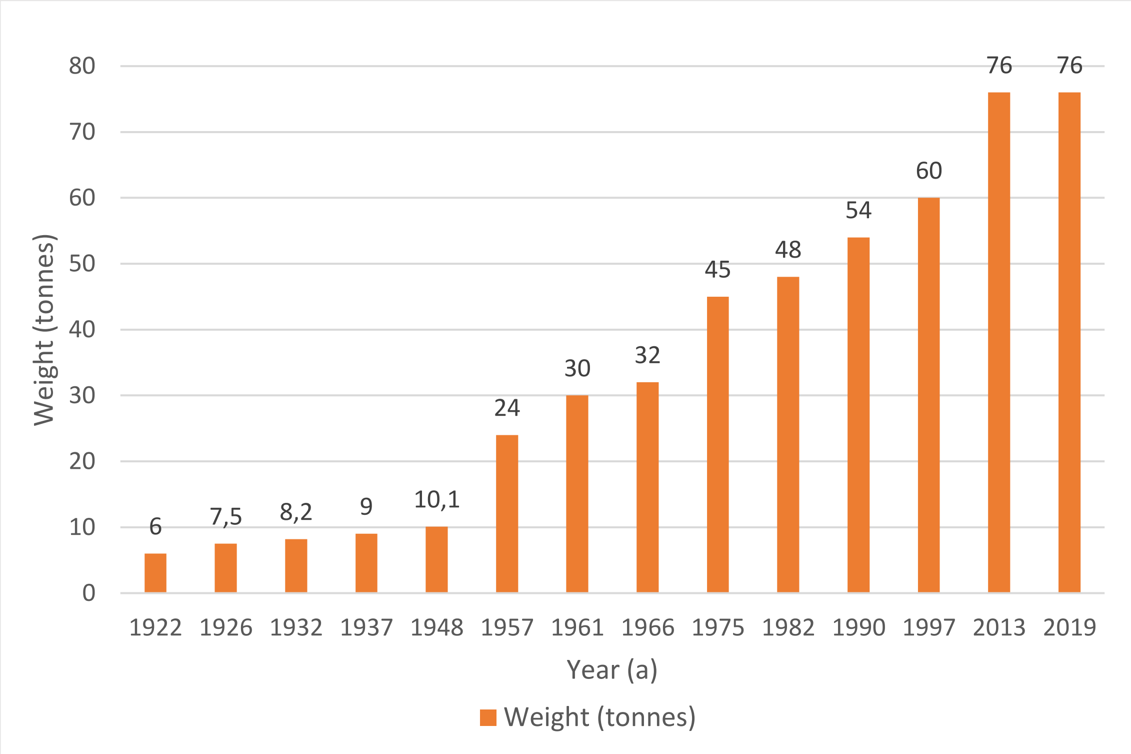

Figure 5. Evolution of Finnish weight legislation for combination vehicles (Source: Ahonen 2015; Finlex 2019)

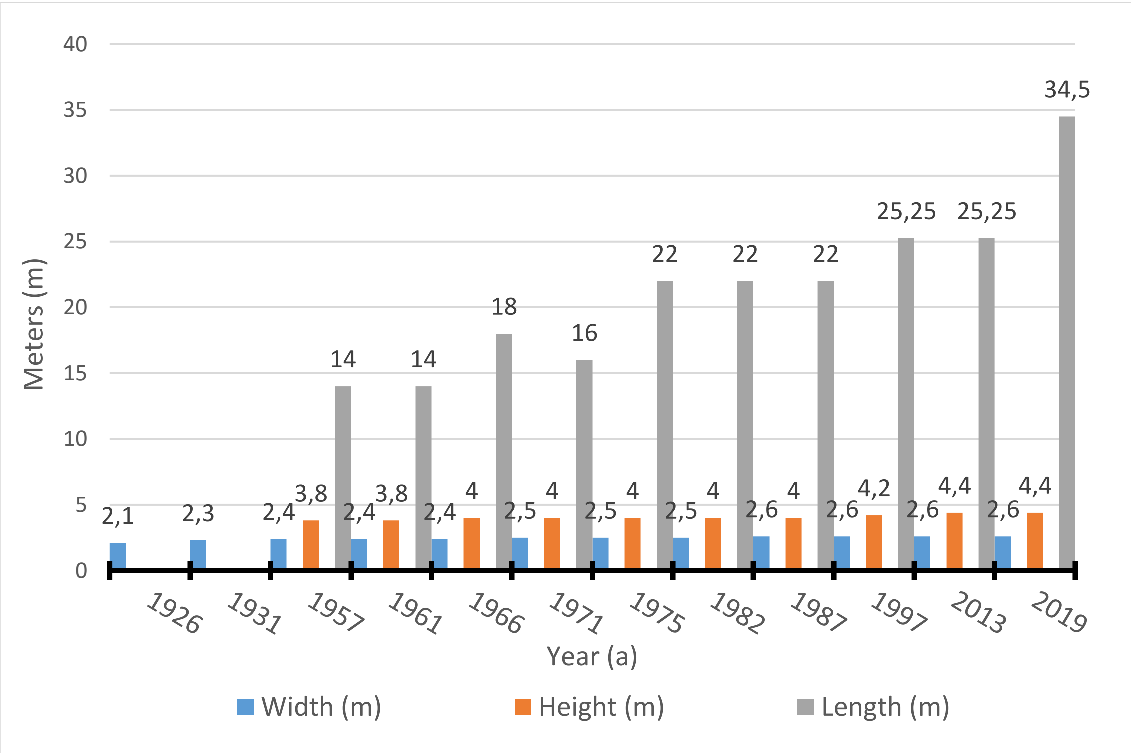

Figure 6. Evolution of Finnish maximum dimensions for vehicles. (Source: Giwed 2016; Finlex 2019)

1.2 Summary on the evolution of Finnish heavy truck legislation.

Notice the upward trend on maximum gross weight and dimensions. The plausible reasons behind the trend: improved design and construct of the vehicles, purpose-built constructions, improved engines and vehicle frames. Increased competition between transport companies and business. Improved infrastructure and due to increased labour costs and grown distances.

1.3 Heavy truck legislation around the world and HCT-vehicle legislation

1.3.1 Introduction to Finnish HCT-Vehicle legislation

The most important change which came with 407/2013 alongside increased dimensions and maximum gross weight, was transport companies were allowed to apply for a permit for so-called "High Capacity Transport-vehicles" (From now on HCT-vehicles). HCT-vehicles were combination vehicles over 25.25 meters long and/or gross weight of over 76 tonnes (Ahonen 2015; Giwed 2016). This definition is outdated at the moment of writing this thesis. After the Government's decree 31/2019, which increased the maximum allowed vehicle length to 34.5 meters (Finlex 2019). Currently, the HCT-vehicle for Finland definition would be "over 34.5 meters long or gross weight over 76 tonnes".

1.3.2 Finnish criteria's for HCT-permits.

According to Matilainen (2018) from Traficom (Finnish transport and communications agency) has the following criteria for HCT-vehicle permits.

"Traficom can allow an exception from regular vehicles maximum dimension and gross weight regulation if necessary" (Matilainen 2018).

The permit has to have the following purposes:

- Experimentation of new technology or transport technics
- Product development

- Other specified reasons

The permit has to follow these criteria's:

- Permit does not to compromise traffic safety
- Permit does not to distort the competition between enterprises

Transport companies apply for HCT-vehicle permits with truck, trailer manufacturers and contractor giver. The application requires a research plan from a research direction, technical data and the planned transport route. After applying, Trafi evaluates the plan with Väylävirasto (Finnish Transport Infrastructure Agency). After evaluation of the research plan, effects on the road network, competition and traffic safety, the application is either accepted or denied. Accepted grants a permit to operate the HCT-vehicle on planned transport road. The permit is temporary, with a length of five years maximum (Matilainen 2018).

1.3.3 Additional research goals

HCT-permits are part of international research and development projects, to increase fuel efficacy and to decrease carbon dioxide emissions (Matilainen 2018). HCT-experiments also aims for increased traffic flow and improved safety, increasing transport efficacy and examine extra-long and extra heavy vehicle's effects on the road network (Ahonen 2015).

2 SUMMARY ON PREVIOUS RESEARCH

2.1 HCT-vehicles and heavy vehicle legislation all around the world.

In this, I am going to introduce other nations' s HCT -experiments, while keeping the main focus on Swedish and Finnish experiments and experiences. It is important to note, that HCT-vehicle's definition varies between nations legislations. While there exist different terms for extra-long and heavy vehicles for example, HCV (High Capacity Vehicle), HPV (High Productivity Vehicles), LHV (Longer and/Heavier Vehicles), LCV (Long Combination Vehicle) (Sjögren *et al.* 2019). For the simplicity, I am going to use the term HCT-vehicle instead of referring to them separately. I am going to only represent examples from nations, where over 25.25 meters and a gross weight of 60 tonnes or over are permitted. This is due to the Finnish and Nordic perspective, where 25.25 and gross weight over 60 tonnes are standard.

2.1.1 Sweden

Sweden's transport industry has been researching and experimenting with extra heavy and long vehicles. Swedish HCT-experiment started in 2009. It is important to note Sweden's legislation on vehicles maximum gross weight and dimensions. At the beginning of Sweden's HCT-experiment, vehicles with a maximum gross weight over 60 tonnes were specified as HCT-vehicles (Suotonen 2017).

Sweden's current HCT-vehicles gross weights and dimensions are consequences from legislative change. Maximum gross weight was increased from 60 tonnes to 64 tonnes in 2015. The next increase came in 2018, which increased the maximum gross weight to 74 tonnes. The current maximum length of the combination vehicle is 25.25 meters. Unlike Finnish legislation, Sweden's legislation does not have maximum height of the vehicle. However, Sweden's transport agency notes the following: "Unrestricted, but roads are generally designed for heights of up to 4.50 meters" (Iru 2013).

Currently, there are two running HCT-experiments in Sweden: ETT, En Trave Till (One Stack More) and DUO2 experiment. ETT-vehicle is used for raw wood long distance transportation. The ETT has maximum gross weight being 90 tonnes and length is 30 meters. Another Project is DUO2, used to transport goods, with a maximum gross weight of 100 tonnes and length 32 meters. (Kyster-Hansen 2013).

Figure 7. Swedish HCT-experiment vehicle. Called En trave till (ETT), “One stack more”. (Source: skogsforsk.fi)

Figure 8. Swedish DUO2 HCT-experiment. (Source: afconsult.com)

2.1.2 Brazil

Brazil’s HCT legislation is summarized in the following sentence: “Brazil normally allows maximum (length) 19.8 meters / (maximum gross weight) 57 tonnes. With special permission and on designated roads, B-doubles up to 30 meters and 74 tonnes are allowed.

There are special requirements for these vehicles, such as tandem operation." (Kyster-Hansen & Sjögren 2013). Maximum height of the vehicles is 4.4 meters and maximum width of 2.6 meters (iru.org 2008).

2.1.3 New-Zealand

Normally permitted trucks in New-Zealand are 20-meters of length, 2.55 meters of width and 4.3 meters of height and 44 tonnes gross weight (New-Zealand Transport agency 2019B). In New-Zealand HCT-vehicles are called: "High Productivity Motor Vehicles" (HPMV) (Kyster-Hansen & Sjögren 2013). For these longer vehicles, there are *Performance-Based Standards* (PBS), which require a vehicle to perform on a certain level on different aspects (New-Zealand Transport agency 2019B). HPMV is only allowed to operate specific routes, while the permits are generally guided towards the increased length of the vehicle. (Kyster-Hansen & Sjögren 2013; New-Zealand Transport agency 2019B).

New-Zealand does not have maximum length for HPMV per se, but for over 25 meters long vehicles need permission from railway operators to cross the railways (Kyster-Hansen & Sjögren 2013). Thus over 25 meters long vehicles do not operate near railways and are very rare. (Kyster-Hansen & Sjörgen 2013). As for 2019, it seems New-Zealand transport agency does not issue new permits for 23 – 25 meter vehicles, due to "lane width issues" (New-Zealand Transport agency 2019A).

Figure 9. Tomoana's HPMV. Length 22.8 meters and gross weight 56 tonnes. (Source: tomoanawarehousing.co.nz)

2.1.4 Australia

Australia's longest allowed vehicle is 26 meters of length and maximum gross weight of 68 tonnes, width with any load is 2.5 meters and height being 4.6 meters. (Kyster-Hansen & Sjögren 2013; Northern Territory Government Information and services 2019). Since 2007, longer and heavier vehicles are under "Performance-Based Standards" (PBS), which do not set a fixed maximum dimension or maximum gross weight, rather acting as a guideline for the vehicle's performance on different road classifications and 16 other safety standards for HCT-vehicles. (Kyster-Hansen & Sjögren 2013). There are examples for road access level and proposed lengths for the vehicles are in table 1 (Sjögren *et al.* 2019).

Table 1. Summary on Australia's HCT-road criteria

Road access level	Permitted routes	Vehicle type	Permitted Vehicle length	Performance criteria
Level 1	Unrestricted road access	Single or Articulated	≤ 20 m	Most stringent
Level 2	Significant freight routes	B-double	≤ 30 m	
Level 3	Major freight routes	A-double	≤ 42 m	
Level 4	Remote areas	A-Triple	≤ 60 m	Least stringent

Figure 10. Australia's so-called "Road train" in Oilbara region. (Source: globaltrailermag 2015)

2.1.5 United States

United States have different legislation guidelines and standards for each individual state. (Kyster-Hansen & Sjögren 2013; Sjögren *et al.* 2019). In this sub-chapter, I am going to present extreme cases and common legislation for federal roads.

The federal maximum gross weight being 80 000 lbs, approximately 36.3 tonnes (Sjögren *et al.* 2019). While the State of Michigan allows 160 000 lbs, approximately 72.5 tonnes. (Michigan traffic agency 2019). As for the dimensions, states typically allow combination vehicles between 65 to 75 feet, 19.8 to 22.8 meters (Sjögren *et al*. 2019). Colorado is an exception, with a maximum length of 35.5 meters. (Kyster-Hansen & Sjögren 2013; Federal highway administration 2015). Maximum width of the vehicles being 102 inches, 2.59 meters. In the United States no federal maximum height legislation exists. The maximum height of the vehicles varies between 13.6 to 14.6 feet, 4.14 to 4.45 meters (Federal highway administration 2015).

HCT-vehicle types in the USA can be divided into three groups:

Rocky mountain double

- A tractor, with two trailers. Long front trailer followed by a shorter trailer.

Turnpike Double

- A tractor, and two long trailers

Triples

- A tractor and three short trailers.

HCT-vehicles are allowed in 23 states. In six of them, vehicles are only allowed to operate as Turnpike double (Sjögren 2019). The future state of HCT-vehicles in the USA is fixed. According to Sjögren *et al.* (2019) HCT are only allowed to operate on specific routes, without being able to expand them or decrease them. HCT-vehicles also have different road and time constraints in different states (Kyster-Hansen 2013; Sjögren 2019). It is safe to say that the USA's HCT-vehicles vary greatly; in their build, size and legislative framework.

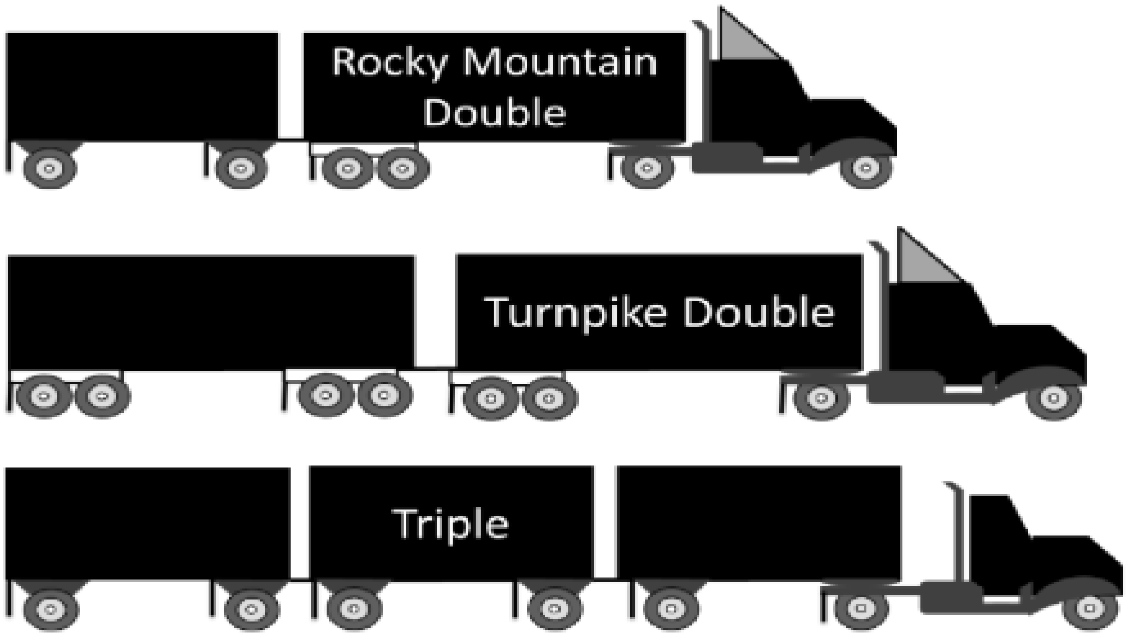

Figure 11. Example of common HCT-vehicles operating in the USA. (Source: Federal highway administration)

Figure 12. Walmart’s Turnpike double. (Source: flickr.com)

2.1.6 Canada

Canada follows the same legislative framework and HCT-vehicles types as the USA: provinces have “considerable” freedom for their legislation. It is important to note that there is a Memorandum of Understanding which is treated as a general guideline for HCT-vehicles and sets the limits for their dimensions and vehicle weights (Kyster-Hansen & Sjögren 2013). The general maximum length of the vehicle is 23–25 meters, the width being 2.6 meters, height 4.15 meters and up to 63.5 tonnes of gross weight, depending on vehicle type and configuration. (Kyster-Hansen & Sjögren 2013).

Some provinces in Canada use PBS, which was originally developed in Canada, but has been adapted in a larger scale in Australia (Sjögren *et al.* 2019). It is important to note that PBS standards between Canada and Australia vary greatly but giving them a deeper analysis is out of the scope of this thesis.

Canada’s specialty on HCT-vehicles is the so-called SPFI (Safe, Productive, Infrastructure-Friendly) standard, which sets special requirements for HCT-vehicles. If the vehicle does not meet these requirements the maximum gross weight of the vehicle is decreased by 3 tonnes. (Kyster-Hansen & Sjögren 2013; Sjögren *et al.* 2019). There seems to be no information available, if vehicles in question are still allowed to operate in such states, which support SPIF-standard.

Canada’s HCT-vehicles have maximum gross weight up to 63.5 tonnes, while exception with B-doubles and A-doubles are sometimes allowed an exception, however this procedure is rare (Kyster-Hansen & Sjögren 2013; Sjögren *et al.* 2019).

Table 2. Guideline for Canada's HCT-vehicle types

Types of the HCT-vehicle	Maximum length (meters)	Gross weigth (tonnes)	Notes
Rocky Montain Double	32	63,5	The maximum length can vary between provinces
Turnpike Double	41	63,5	
Triples	35	53,5	

2.1.7 Mexico

Mexico's HCT-vehicle legislation is based on road class, which vehicles are operating. Current road classes are as follows (Sjögren *et al.* 2019):

• ET Highways (Transportation axis) is the highest class
• A Highways, high standard, part of the primary road network
• B Highways, lower standard than type A, but still associated with the primary road network
• C Highways, secondary network, which connects to, and connects different parts of the primary network
• D Highways, a feeder road network, primarily in more urban areas

Mexico's maximum length of the vehicle is 31 meters and a gross weight of 66.5 tonnes. Dimensions of the vehicles are depending on previously mentioned road classification, varying between 4.15 meters of height and 2.6 meters of width. (Mexico's traffic ministry 2006).
HCT-vehicles are only allowed to operate on ET-, A-, B-, class highways, where using longer semi- and trailers are allowed. (Kyster-Hansen & Sjögren 2013). HCT-vehicle types are usually Doubles and B-doubles. Previously vehicles up to 36 meters and gross weight of 81 tonnes were allowed before the decrease (Kyster-Hansen & Sjögren 2013; Sjögren *et al.* 2019). This was due to concerns on infrastructure damage and accidents, which have claimed 40 persons as victims according to Mexicotrucker (2013).

2.1.8 South Africa

South African HCT-vehicles are based on PSB. The current normal maximum vehicle length is 22 meters with a gross weight of 56 tonnes. Dimensions being 2.6 meters in width and height of 4.3 meters (Transport department of the Republic of South Africa 2009; Kyster- Hansen & Sjögren 2013). South African PBS-standard permits on levels 1 to 2 length up to 30 meters and gross weight between 56.2 and 82 tons (Sjögren *et al.* 2019). On the PBS levels 3 to for, it is possible to operate a vehicle with the length of 42.8 meters and maximum gross weight of 185 tonnes.

2.2 Summary of HCT-vehicles and around the world

Many countries have their experiments or legislative framework for HCT-vehicles. The maximum length varies between 25 and over 60 meters, while maximum gross weight can be up to 100 tonnes. As a general HCT-vehicles have a legislative framework as either PBS, SPFI or as separately applied permissions. HCT-vehicles usually operate on bigger road networks, commonly operating on set roads and highways set by the government. Usually, besides the Nordic countries, the focus of HCT-vehicles is on increased vehicle length. Although increased maximum gross weight HCT-vehicle does exist around the world. When comparing normal maximum dimensions and gross weight, in the Nordics gross weight seems to be more the focus. Summary of the normal dimensions, gross weights and HCT-legislation are in table 3.

Table 3. Normal gross weights, dimensions and HCT-legislation

Coun-try	Gross weight	Lengt h (m)	Width (m)	Height (m)	HCT-legislation	Notes
Finland	76	34,5	2,6	4,4	Permission-based on vehicle weight/experiment	
Sweden	74	25,25	2,6	4,5*	Permission-based/experiment	*No set maxi-mum height
Brazil	57	19,8	2,6	4,4	Permission-based	
New-Zealand	44	20	2,55	4,3	High Productivity Motor vehicle -standards	
Aus-tralia	68	26	2,5	4,6	Performance based -standard	
United States	36,6 / 72,5	19,8 / 35,5	2,59	4,14 / 4,45*	Varies greatly between states	*No set maxi-mum height
Canada	63,5	23 / 25	2,6	4,15	Memorandum of Understanding / Performance based -standard / SPFI -standard	
Mexico	66,5	31	2,6	4,15	Based on road classification	
South-Africa	56	22	2,6	4,3	Performance based -standard	

3 HCT-STUDIES

3.1 Introduction to HCT studies

All the countries mentioned in the previous chapter have conducted their HCT-research, considering previously mentioned research goals. HCT-studies consist on potential savings, fuel efficacy and impacts on traffic safety and infrastructure. This chapter examines through studies across the world, while keeping the focus on the Finnish and Swedish research, especially in the forestry field.

3.1.1 Potential savings when utilizing HCT-vehicles

With the current cost structure of the transport companies', where the major sources of costs are fuel, labour and capital, introducing heavier/longer HCT-vehicles may bring substantial savings for transport company (Sjögren 2019), due to HCT-vehicle's increased payload both in weight and volume compared to regular-sized vehicles. (Venäläinen 2019; Sjögren *et al.* 2019). According to Panteia (2018), over 60 % of transport companies' costs came from labour and fuel. Thus when transport companies introduce HCT -vehicles into their vehicle fleet, the biggest economical possibilities are made in labour and fuel expenses, as the same transport operations can be made with lesser use of vehicles, labour and fuel (Sjögren 2019).

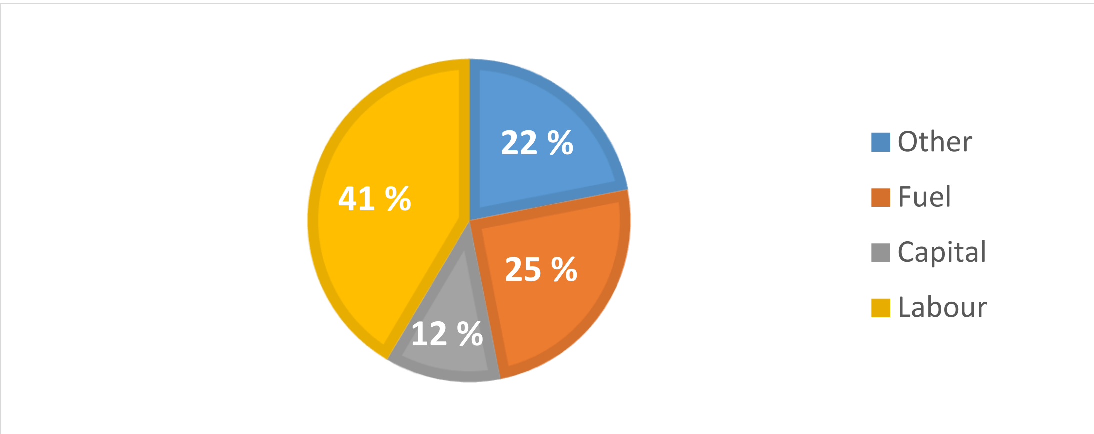

Figure 13. The cost structure of transport companies in Austria, Belgium, Denmark, France, Germany, Great Britain, Italy, the Netherlands, Norway, Spain and Sweden. (Source: Panteia 2018).

3.1.2 Savings in labour costs

Savings in labour costs are an important reason for Finnish transport companies to introduce HCT -vehicles as part of their fleet. This is due to the small size of the companies, most of them belonging small- to average size companies and lack of skilled drivers (SKAL 2019) and relatively high income of average driver (Broughton 2015) compared to other European countries. This is observed especially when conducting long-distance transport operations in the forestry field, being 110 kilometres in 2017 (Strandström 2018).

According to Sweden's DUO2 HCT-experiment, when comparing regular 16.5 -semi-trailer and 25.25 combination vehicle to DUO2 combination vehicle, while hauling cargo with volume of 600 cubic meters and density of 150 kilograms per cubic meter, it is possible to cut down labour need from 6 or 4 to 3 (DUO2.nu 2019). According to Finnish HCT-experiments by Venäläinen (2019) "More efficient haulages decrease the need of labour in carrier companies". It is important to note that with the increased haulage efficiency may lead to an improvement in industries' employment.

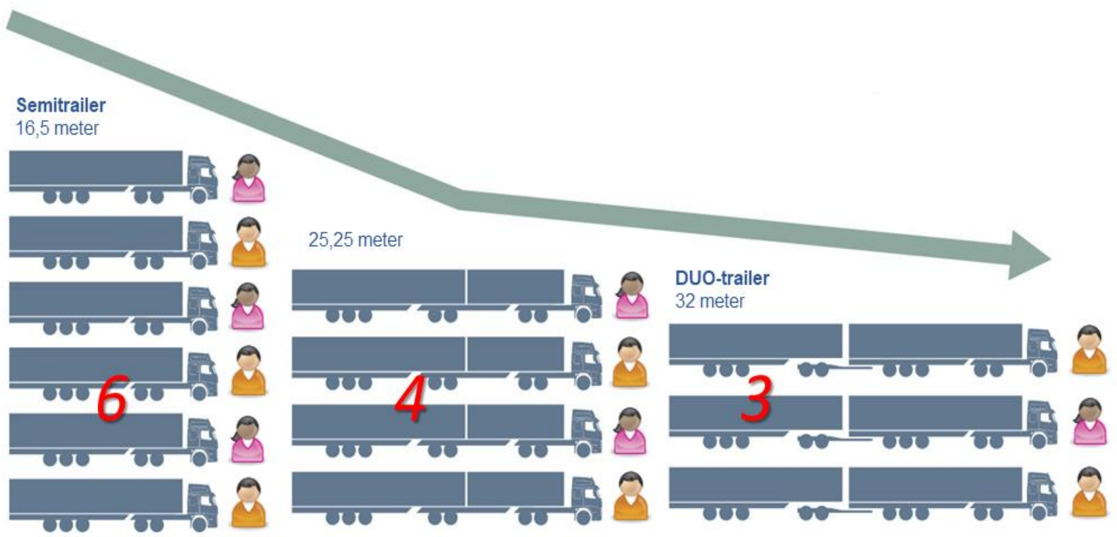

Figure 14. Swedish's calculations on the effects of HCT-vehicles on required labour. (Source: DUO2.nu 2019)

3.1.3 Increase with fuel efficacy

In her report, Venäläinen (2019) states the following: “If the combination vehicle’s length increases, while total gross weight stays the same, we can assume that fuel efficiency improves for the transported amount of goods.” However, Venäläinen notes that increased vehicle’s tare weight might require more axles on a vehicle, thus decreasing the fuel efficiency (Venäläinen 2019). This is due to increased wind and rolling resistance.

In Canada’s HCT-experiment, use of longer and heavier vehicles allowed up to 32 % of savings in fuel consumptions and 29 % reduction in cost while comparing it to the United States 36.6 tonnes tractor semi-trailer combination vehicle. However, it is important to note that calculations did not take account operational patterns or operational environment (Woodrooffe 2016). In Sweden’s Duo2 experiment, using DUO2 HCT-vehicles had 12 % savings in fuel consumption for every transported cubic meter of cargo while comparing to 25.25-meter-long combination vehicle (DUO2.nu 2019). In the Finnish forestry field, utilizing 84 tonnes of HCT-vehicle instead of 76 tonnes normal vehicle, in transport between roadside and target leads to 10 % in fuel consumption. When comparing the transports between terminal and target, the difference can be up to 20 % (Venäläinen 2019). More scenarios and calculations on fuel consumption in the forestry field are presented in figure 15.

The opposite effect on the total fuel consumption is possible. It is possible to increase the total fuel consumption when introducing HCT-vehicles into the traffic if HCT-vehicles cause shift from rail transports to road transports due to modal shift (Knight *et al.* 2008). When inspecting situation on the forestry field, it could be very likely situation. Due to long transport distances in Nordic countries, especially in Finland and Sweden and the current state and future of railroad network (Lapp & Tiikkanen 2017).

It is important to note the meaning of the percentages in the figure 15. Heavier and longer HCT-vehicles can be loaded either form the ground or be attached with a pre-loaded semi- or trailer. Percentages represent amount of from ground loaded cargo (Poikela & Venäläinen 2017).

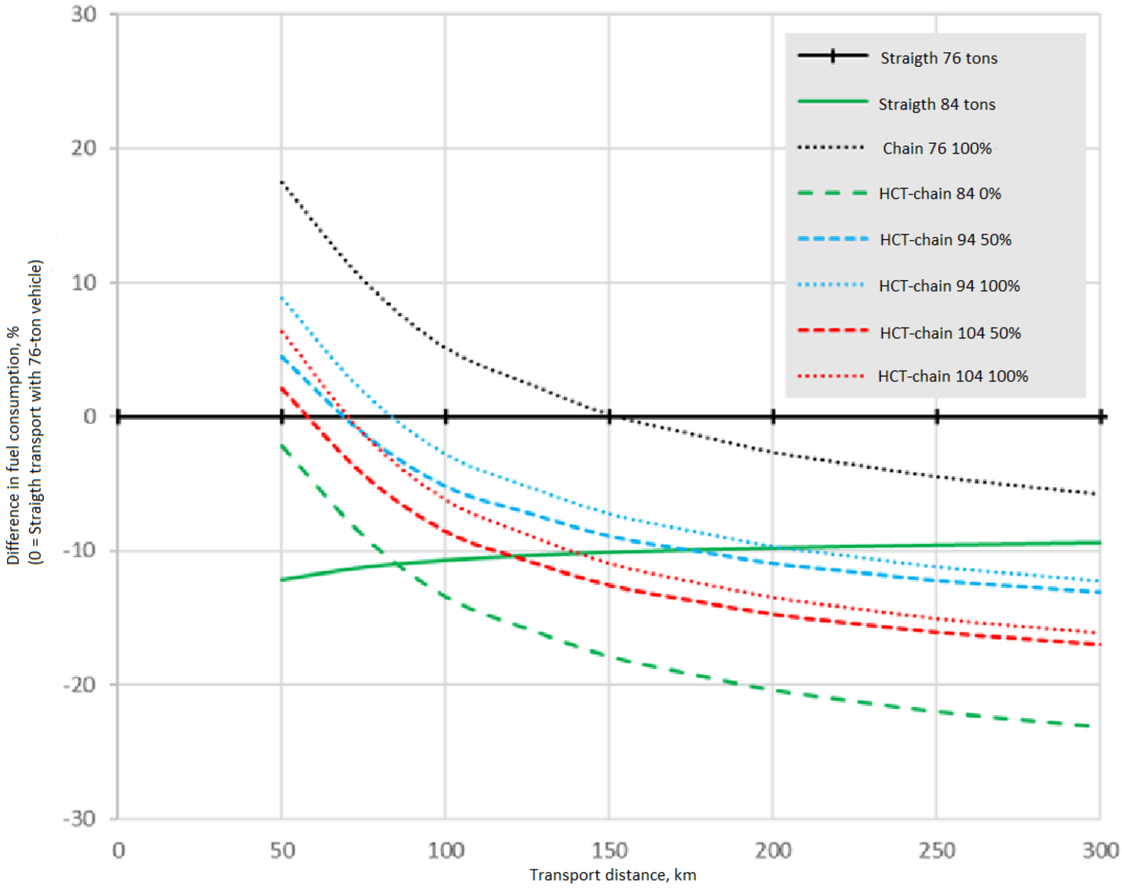

Figure 15. Difference in fuel consumption when transporting comminuted energy wood with different vehicles and supply chains. (Source: Venäläinen 2019)

On the differences in fuel consumption. Venäläinen (2019) notes: "Fuel consumption depends on many different aspects, such as differences in elevation". Due to this, calculations are based on comparison vehicles, which are operating on the same routes and may not represent the situation as whole.

3.2 Transport costs with HCT-vehicles

Due to previously mentioned improved increases on the fuel- labour efficacy. With the increased payload volume, utilizing HCT-vehicles have substantial saving-potential (Venäläinen 2019; Sjögren 2019). According to Sjögren (2013) HCT-vehicles can reach up to 23.9 percent increase in transport economy, if all timber transports and 5 % of conventional transports are done by HCT-vehicles.

In the forestry field, when comparing 60 tonnes regular timber truck and 90 tonne ETT-vehicle in the transportation of 1000 tonnes of timber payload, ETT was 23 % more cost efficient to operate (Löfroth & Svenson 2012). In the Finnish HCT-experiments, the similar results in calculations were obtained (Venäläinen & Korpilahti 2015). Closer cost comparison in the Finnish timber transportation is presented in figure 16.

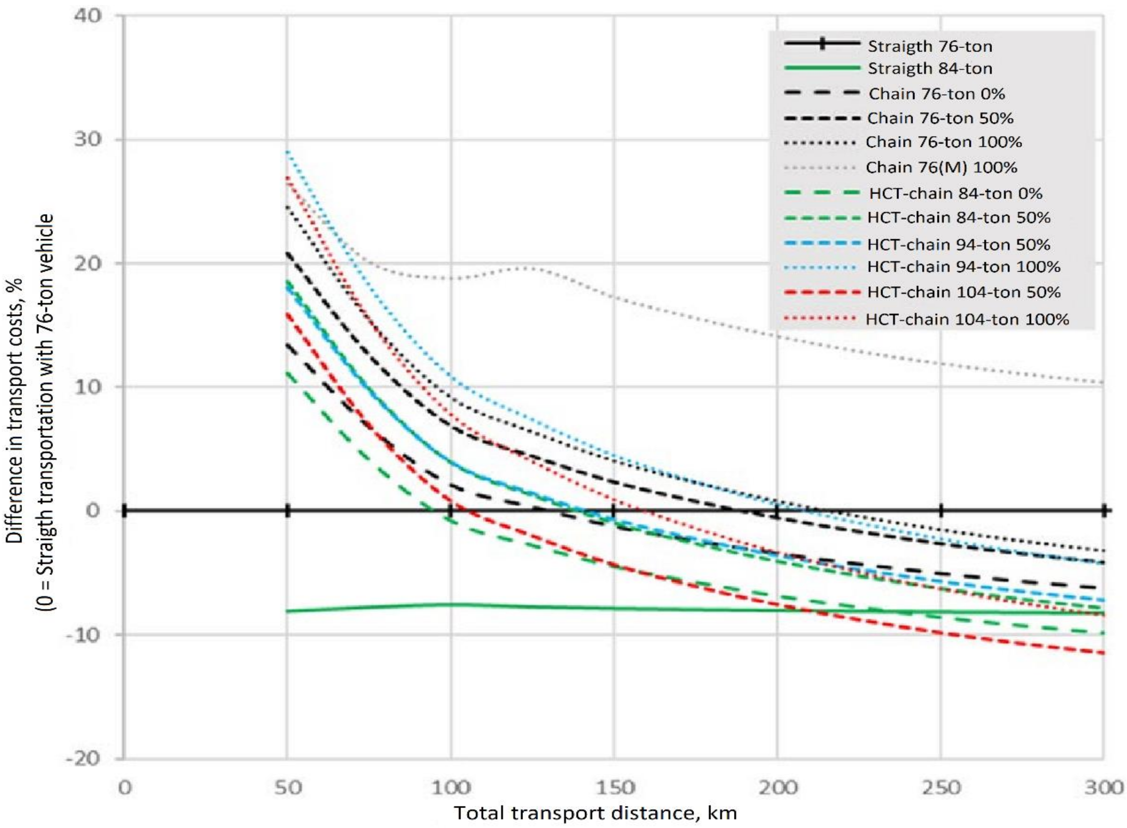

Figure 16. Different timber's transport chains' cost differences over different distances (Source: Venäläinen & Poikela 2019)

We can notice that all HCT-transport chains are cheaper than to regular 76 tonnes vehicle, when transport distance exceeds 200 kilometers and for some transport chains, the break-even point occurs before 150 kilometers. It is important to note that just inspecting transport costs do not represent the situation. Investments may be necessary in infrastructure: roads, pavements, bridges and possible arrangements of loading and unloading areas to be able to accede such vehicles (Venäläinen 2019).

3.3 Summary of economic impacts of HCT-vehicles

Biggest part most of the transport companies' costs are from fuel and labour. HCT-vehicles can bring substantial savings and efficacy increase to transport industry. The increased payload weight and volume decreases the amount of required labour and thus lower labour costs. Furthermore HCT-vehicles may consume up to 23 % less fuel when compared to a regular size vehicle per transported tonne. In timber transportation HCT-vehicles are very competitive for transport distances more than 150 kilometers when compared to regular-sized vehicles.

3.4 HCT-vehicle's impacts on traffic- safety and flow

One of the main concerns of increasing maximum vehicle dimensions and weights is effects on road safety. In the next chapters, I am going to examine HTC-vehicles on behalf of road safety.

3.4.1 HCT-vehicles in accidents in Finland between 2016 - 2018

According to the Finnish HCT-experiment's steering groups reports between 2016 and 2018, HCT-vehicles have been in several accidents, of -which some claimed casualties. Fatal accidents were collisions between HCT-vehicles and other vehicles. The HCT-vehicle's drivers were declared innocent to all the accidents (Lahti & Tanttu 2018). The noteworthy second fatal accident happened, when a passenger car crashed straight forward to an incoming HCT-vehicle's tractor. The HCT-vehicles driver did not suffer any injuries and was declared innocent to the accident. Police suspects suicide (Lahti & Tanttu 2017B).

Other non-fatal accidents happened mainly due to human error, without the fault on the HCT-vehicle's driver (Lahtinen & Tanttu 2018). Some accidents were caused by deers, which crashed with HCT-vehicle (Lahti & Tanttu 2017A) and the HCT-vehicle's hindmost trailer fell over into a ditch, after correction movement (Lahti, Tanttu, Trafi 2016).

According to the steering groups' reports, it could be argued, that HCT-vehicles have not been in any accidents caused by increased length or weight of the HCT-vehicle. Most of the HCT-vehicle drivers have reported, that the majority of the "close calls" are due to overtaking vehicle's driver's failure to asset the required time and the required distance to overtake the longer HCT-vehicle (Lahtinen & Tanttu 2017B).

3.4.2 HCT-accident in research

Longer combination vehicles are proven statistically to be less likely to take part in an accident (Heinonen 2017). According to the report "*High Capacity Transport: Towards efficient, safe, and sustainable road freight*" (Sjögren, Aronetis, Voege 2019) where HCT-vehicles reported lower accident rates than regular vehicles on countries where on use. It is important to note that comparing regular-sized and HCT-vehicles is difficult, due to onboard technology, more skilled drivers, limited operating areas and regulatory framework and environment (Sjögren, Aronetis, Voege 2019). Heinonen (2017) notes how previously mentioned studies do not take into account the road types and traffic conditions where HCT-vehicles mainly operate, the HCT-vehicle's drivers experience- or skill levels. Due to this, absolute values for HCT-vehicle's probability to get into accidents are complicated to analyze. Heinonen does state the following: "*…studies had consensus on vehicles are not only affected by the length of the vehicle and gross weight but rather; vehicle's type (for example number of trailers), road class and the properties of driver"*.

3.4.3 HCT-vehicles impact on traffic flow

Longer and heavier vehicles have an impact on traffic flow. This is due to longer vehicles take up longer stretch on the road and maximum travel speed is lower (Finlex 2018), and their incapacity to keep up with other vehicles travel speed up in hills and at turning points (Heinonen 2017). Meeting the longer and heavier vehicle may cause more psychological stress on smaller vehicle's drivers, leading to excessive risk-taking behavior (Summala *et al.* 2003). This is the reason to examine HCT-vehicles impact on the traffic flow.

3.4.4 HCT-vehicles in overtaking situations.

Heinonen (2017) compared 33, 34.5 and 31-meter-long HCT-vehicles with their corresponding regular vehicles. Heinonen analyzed impacts on overtaking situations: overtake times-, speed-, type-, vehicles and queueing times. Summary of Heinonen's results is presented in table number 4.

Table 4. Summary on Heinonen (2017) results from his research

Survey component	Result	Discussion
Number of overtakes	Minor increase with HCT-vehicles	No statistically significant increase. Depends on traffic level
Type of overtake	No difference between regular and HCT-vehicles	No significant difference. Depends on traffic level and route
Time spend overtaking	Overtaking HCT-vehicle takes one second longer on average	Statistically significant difference. Lower than theoretically calculated difference
HCT-vehicle's distance travelled while overtaking	HCT-vehicles travel 14 - 18 meters longer than regular vehicles	Statistically significant difference. Similar results to time spend overtaking
Overtaking vehicles distance traveled	Overtaking vehicle travel 23 - 24 meters longer distance while overtaking HCT-vehicle	Statistically significant difference. Similar results to time spend overtaking
HCT-speed while being overtaken	1 - 6 km/h lower than regular vehicles	Statistically significant difference. Lowered time spend overtaking
Overtaking vehicles' speed	Increased speed while overtaking HCT-vehicle	No statistically significant result
Safety times	Increased safety times	Statistically significant results. Negative correlation between traffic level

When comparing different components of overtaking situations, minor differences can be observed in every survey component. It is worth noting, that only a few components have a statistically significant difference. Many component's results are independent of HCT-vehicles qualities, rather on traffic levels on the HCT-operating routes and actions of overtaking vehicle's drivers.

3.4.5 Queueing with HCT-vehicles

Heinonen also studied queuing lengths and times with HCT-vehicles and compared the corresponding regular-sized vehicles. Heinonen's (2017) results are reported in table 5.

Table 5. Summary on Heinonen (2017) results on HCT-vehicles impact on traffic flow

Survey component	Result	Discussion
Frequency of long (over 3 vehicles) queues	Majority of queues under 3 vehicles	Queueing is not an issue
Average length of queue	Increased queue length with HCT-vehicles	Minor increase, more depended on traffic level and operating hours
Follow up-time	11 - 39 seconds longer with HCT-vehicles	No statistically significant result

On average, queueing studies did not show significant results on the negative impact on traffic flow. Heinonen (2017) states: "*Results as in whole give some implication that other drivers have to queue for longer periods while waiting for an opportunity to overtake HCT-vehicle*".

3.5 HCT-vehicle's stability

Higher, heavier and longer HCT-vehicles can act uncontrollably in traffic, when comparing to regular sized vehicles. Thus to investigating stability is one of the key aspects on permitting HCT-vehicles to operate in a larger scale on road network. From Oulu University, Mechanical engineering, Pirnes *et al.* (2018) have made research on the topic.

In their research, Pirnes *et al.* (2018) inspected one HCT-vehicle with 104 tonnes of gross weight and total length of 33 meters. The other HCT-vehicle was 84 tonnes of gross weight and 24,3 meters of length. The 104 tonnes vehicle consist of 4-axle tractor, 4-axle semi-trailer and 5-axle trailer. 84 tonnes vehicle consist of 5-axle truck and 5-axle trailer. Their results are summarized in table 6.

Table 6. Summarized results from Pirnes *et al*. (2018) research on stability

Survey component	Criteria	Results
Mobility	Slipping of tires, ability climb hills	Performance aquate, some slipping when empty or climbing a hill
Stability	Increased frequency of higher lateral acceleration	Slightly increased frequencies
Braking	Braking distance	On average 10 % longer than 76 tonnes vehicle

When inspecting table 6 on mobility, stability and braking, Pirnes *et al*. (2018) do state the mobility to be adequate for normal traffic conditions, slipping of tires being very rare occasion. What comes to stability, HCT-vehicles did have more frequent higher lateral acceleration, which could lead to loss of the control of the vehicle. It has to be noted that, 84 tonnes HCT-vehicle was more unstable than 104 tonnes HCT-vehicle. However, Pirnes *et al* (2018) do not state anything on the state of the matter. With breaking distances, HCT-vehicles are substantially heavier and longer than regular vehicles, thus they have increased breaking distances.

3.6 HCT-vehicles effect on road wear

Being heavier and longer than normal-sized vehicles, HCT-vehicles effects on road wear have to be inspected, before permitting them to operate on road networks. There is not yet any conclusive research on the topic at the time of writing this thesis (Metsäteho 2020). One research consisting some insights on HCT-vehicles' effect on road wear: Sauna-aho *et al.* (2018) have been researching the topic for the Finnish Transport Infrastructure Agency.

Road wear can be measured using equivalent axle number. One unit of equivalent axle equals road wear of one 10 tonnes axle equipped with twin tires. Road wear for the whole vehicle is determined with sum of all axles on the vehicle according to their structure: Number of axles, tires, type of suspension etc (Sauna-aho *et al.* 2018). Equivalent axle number is then divided by the payload, when comparable results come in. Sauna-aho *et al.*'s (2018) results are presented in the table number 7.

Table 7. Sauna-aho *et al (2018)* results from road wear calculations on regulated roads

Vehicle	Gross weight	Tare weight	Axle groups	Axles in total	Axles with single tires	Number of tires	Axle equivalents	Payload per axle equivalent
#	Kg	Kg	pcs	pcs	pcs	pcs	pcs	Tonnes/equivalent axle
1 (norm-VEH)	38340	15881	3	6	5	14	1,84	12,77
2 (norm- VEH)	68000	25499	4	8	7	18	6,65	6,39
3 (HCT- VEH)	87400	31140	5	11	10	24	7,4	7,61
4 (norm- VEH)	77000	25269	4	9	2	32	4,61	11,23
5 (HCT- VEH)	94000	28385	5	12	3	42	4,35	15,09
6 (HCT- VEH)	82740	26027	5	11	1	42	2,87	19,76
7 (HCT- VEH)	81320	24337	5	11	9	26	5,54	10,28

We can notice how HCT-vehicles' axle equivalent values are lower than normal vehicles. Sauna-aho (2018) states: "HCT-vehicles cause 0.63–0.84 times the road wear, when transporting the same amount payload." On the note, utilizing HCT-vehicles should decrease the road wear, if adopted on a large scale. Especially if axles are equipped with twin tires.

3.7 Summary of previous research

HCT-vehicles and corresponding changes in legislation have been a great addition to transport companies' fleet and Finnish transport industry. HCT-vehicles have proven to be more cost efficient on labour and fuel costs and are not statistically proven to risk traffic safety or congest traffic flow. As with mobility and stability, HCT-vehicles do not differ significantly from normal-sized vehicles. With the road wear, results are unclear. HCT-vehicles cause less stress on the roads, when measuring with axle equivalent numbers, but effects on multiple HCT-vehicles operating regularly on the same route, is unclear.

4.0 DEFINING THE RESEARCH TOPIC

4.1 Background for the research topic

After the Finnish government's decree 31/2019 maximum length of the vehicle was raised to 34.5 meters while keeping the maximum gross weight the same. All of the previous research and experiments were conducted with over 25.25 meters long and gross weight over 76 tonnes HCT-vehicles, thus knowledge on just increased vehicle length but constant gross vehicle weight is lacking.

HCT-vehicles as an experiment, have been an integral part of the modern Finnish transport industry. In the Finnish forestry, where transport distances and costs can be argued to be higher than with other industries. HCT-vehicles have been widely utilized in terminal-based operations. To utilize the increased load volume, made possible by increased maximum length, with increased tare weight, is hard in forestry field for the most transported assortments round wood and wooden chips. Increased payload volume is hard to utilize as the weight limit is reached before the maximum load volume. Thus the government's decree 31/2019 is hard to utilize in Finnish forestry.

The goal of this thesis is to examine possible opportunities to utilize over 25.25 meters of length and 76 tonnes HCT-vehicles in forest energy wood transportation, the possible savings in costs structures and to increase its competitiveness in the energy market and thus aid Finland reaching its energy policies goals.

4.2 Research question

The main research question of the thesis is to inspect new possibilities for utilization in the forestry field forestry energy wood transportation with HCT-vehicles, according to government's decree 31/2019.

Axiom of the thesis are:

- Increased vehicle length decreases maximum payload weight. Increased vehicles length increases the required number of axles and necessary equipment and structure, thus increasing the tare weight of the vehicle and decreasing maximum payload weight.

Postulates of the thesis are:

- What is the economically most viable distance to transport energy wood with HCT-vehicle?
  - What is the break-even distance and how does this compare to “normal” 25.25 meters long vehicle?
- What is the most rational energy wood type to transport with HCT-vehicles?
  - Energy wood can consist of different types of energy wood, from delimbed small diameter to harvest residuals.
  - Are HCT-vehicle more efficient in transporting comminuted or uncomminuted energy wood?
- What are the optimal dimensions and constructs of an HCT-vehicle for energy wood transportation?
  - This includes aspects as maneuverability and load ability.

Hypothesis are:

- Transporting comminuted or chipped energy wood with HCT-vehicles is less cost-effective than transporting it with normal size vehicle.
- Transporting uncomminuted energy wood with HCT-vehicles is an economically more viable option
- Moisture content of the energy wood affects greatly viability of HCT-vehicles usage with comminuted and uncomminuted energy wood.

5 ENERGY WOOD SUPPLY CHAIN AND USAGE

5.1 Introduction to the energy wood supply chains and usage

To understand the potential impacts of introducing HCT-vehicles into forest energy woods supply chain, we have to take a look at forest energy wood types, usage and cost structure.

5.1.1 Energy wood harvesting

Forest energy wood consist of four different wood types (Koistinen *et al.* 2016):

- Small-diameter wood
  - Harvested as delimped or as the whole tree from final fellings and thinning's. Can be harvested as integrated or sole timber grade. Transported to roadside for drying.

- Harvest residuals
  - Typically branches of Norway spruce (Picea abies) from final fellings. Usually left to dry on wood lot, until fall off. Collected and transported using forwarder to the roadside.

- Tree stumps
  - Harvested typically from Norway spruce dominated stands after final felling. Stump is comminuted into parts and lifted using excavator with stump dipper. Transportation to the roadside using a forwarder.

- Coarse stem wood
  - Collected typically during the harvesting from thinning's and final felling's. Harvested using harvester and forwarded to the roadside with the forwarder. Usually of a low quality that cannot be utilized for was logs or pulp wood.

According to Koistinen *et al.* (2016) energy wood harvesting should be focused on more nutrient-rich soils and wood lots, due to potential negative effects on nutrient content, vegetation and growth. Exception is root rot infested wood lots, where stump harvesting should be considered to decrease the risk of infection of the following generation.

Figure 17. Harvest residuals at roadside. (Source: Metsälehti)

5.2 Energy wood usage in Finland

In 2017 the total usage of energy wood in Finnish CHP- plants and residential buildings were 7.8 milj. m3, 15.7 TWh in energy and corresponding values according to user were 7.2 mil.m3 (14,4 TWh) and 0.7 milj.m3 (1,3 TWh) (Strandström 2018). Shares of the energy wood (Suomen virallinen tilasto 2019) were the following:

- Small-diameter wood: 4.4 million cubic meters
- Harvest residuals: 2.5 million cubic meters
- Tree stumps: 0.5 million cubic meters
- Coarse stem wood: 0.4 million cubic meters

When assuming 0.5 milj.m3 ~ 1 TWh corresponding energy values were:

- Small-diameter wood: 2.2 TWh
- Harvest residuals: 1.2 TWh
- Tree stumps: 0.3 TWh
- Coarse stem wood: 0.2 TWh

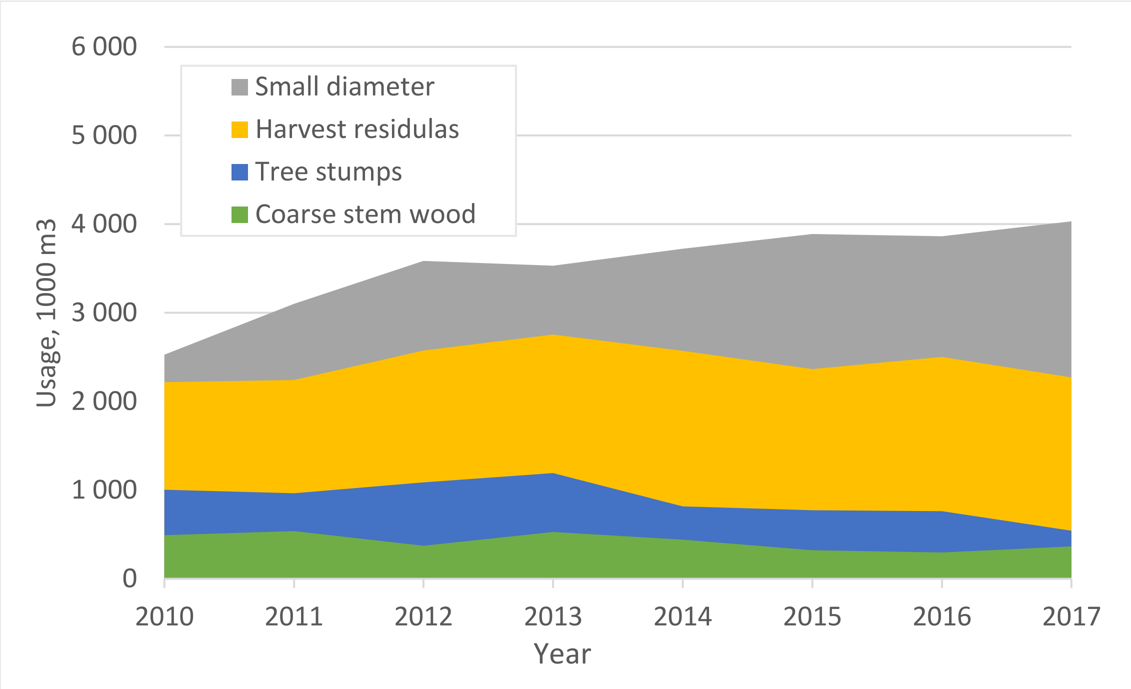

Figure 18. Usage of forest energy wood of Finland in CHP-plants 2010–2017. (Source: Natural resource instate Finland)

When examining the usage of different energy wood types, small diameter wood and harvest residuals are the dominant ones. This is due to ease of harvesting; comparing with tree stumps and coarse stem wood, small diameter and harvest residuals can be harvested in large scale with regular harvesting techniques and technologies. Coarse stem wood is often used for pulp wood. Coarse stem wood is used for energy wood when quality is so bad, that it is unacceptable as pulp wood. Harvest residuals and small diameter wood have better combustion properties: more even quality, fewer foreigner objects and the ease of storing.

5.4 Energy wood supply chains

Energy wood is chipped into wooden chips before combustion, due to its increase in fuel charismatics (Koistinen *et al.* 2016). Supply chains can be divided into four categories (Strandström 2018):

- ***Chipping on a wood lot***
  - Chipping done on the wood lot: either from bundles or loose energy wood transportation to the terminal or final user as wooden chips.

- ***Chipping at a roadside***
  - Chipping done on wood lot's roadside: either from energy wood bundles or loose energy wood. Transportation to the terminal or final user as wooden chips.

- ***Chipping at a terminal***
  - Energy wood transportation as bundles or loose residue and chipping at the terminal.

- ***Chipping at final user***
  - Transportation as bundles or loose energy wood and chipping at the final user.

In 2018, the most common supply chain was roadside chipping (54 %), the second was terminal chipping (35 %), and followed by chipping at final user chipping (10 %) and the least common was wood lot chipping, which is not in widespread use in Finland (Strand-ström 2019). The proportions of the different energy wood supply chains between 2000 and 2017 are presented in figure 19.

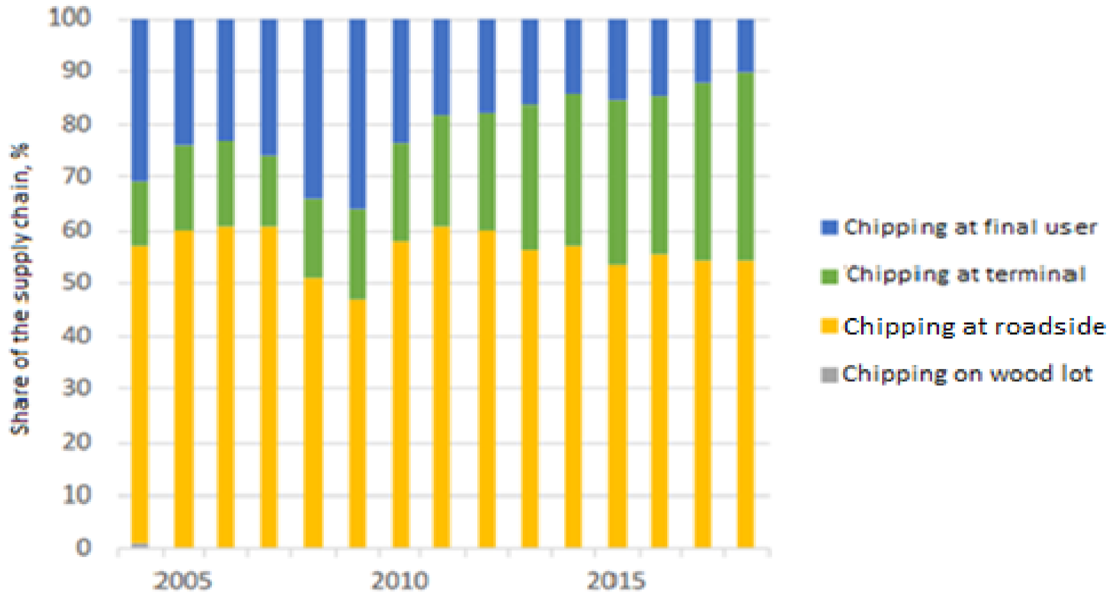

Figure 19. Proportions of forest energy wood supply chains in Finland between 2005 and 2017. (Source: Strandström 2018)

5.4 Cost structure with energy wood

According to Laitila *et al*. (2010) energy wood's cost structure can be divided in to:

- Stumpage prize
- Harvesting: fellings, bundling, stump lifting, forwarding, piling
- Chipping: at a terminal, roadside, the final user
- Transportation costs
- Organization costs

Laitila *et al.* (2010) studied the cost structure of energy wood supply chains. Their results are presented in figure 20.

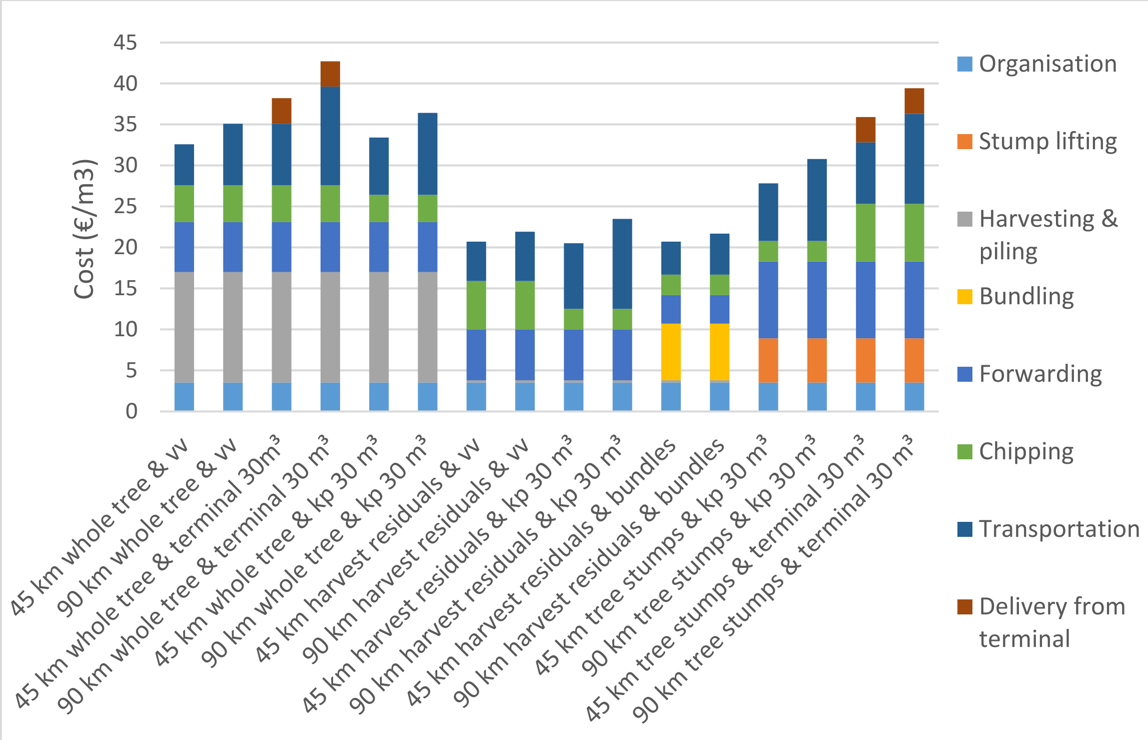

Figure 20. Cost structure of forest energy wood in Finland. (Source: Laitila *et al.* 2010)

According to Laitila *et al.* (2010), for the whole tree assortment, the majority of the costs are from the harvest (37–41 %). For harvest residuals, the majority of costs come from transportation (23–46 %). With tree stumps, the most cost intensive part of the supply chain is stump lifting and transportation (20–32 %).

The proportion of the transport component for the different forest energy wood assortments can be explained physical properties. Stumps and harvest residuals are very bulky and light cargo to transport. Thus, loading transport vehicles up to their full payload weight is difficult.

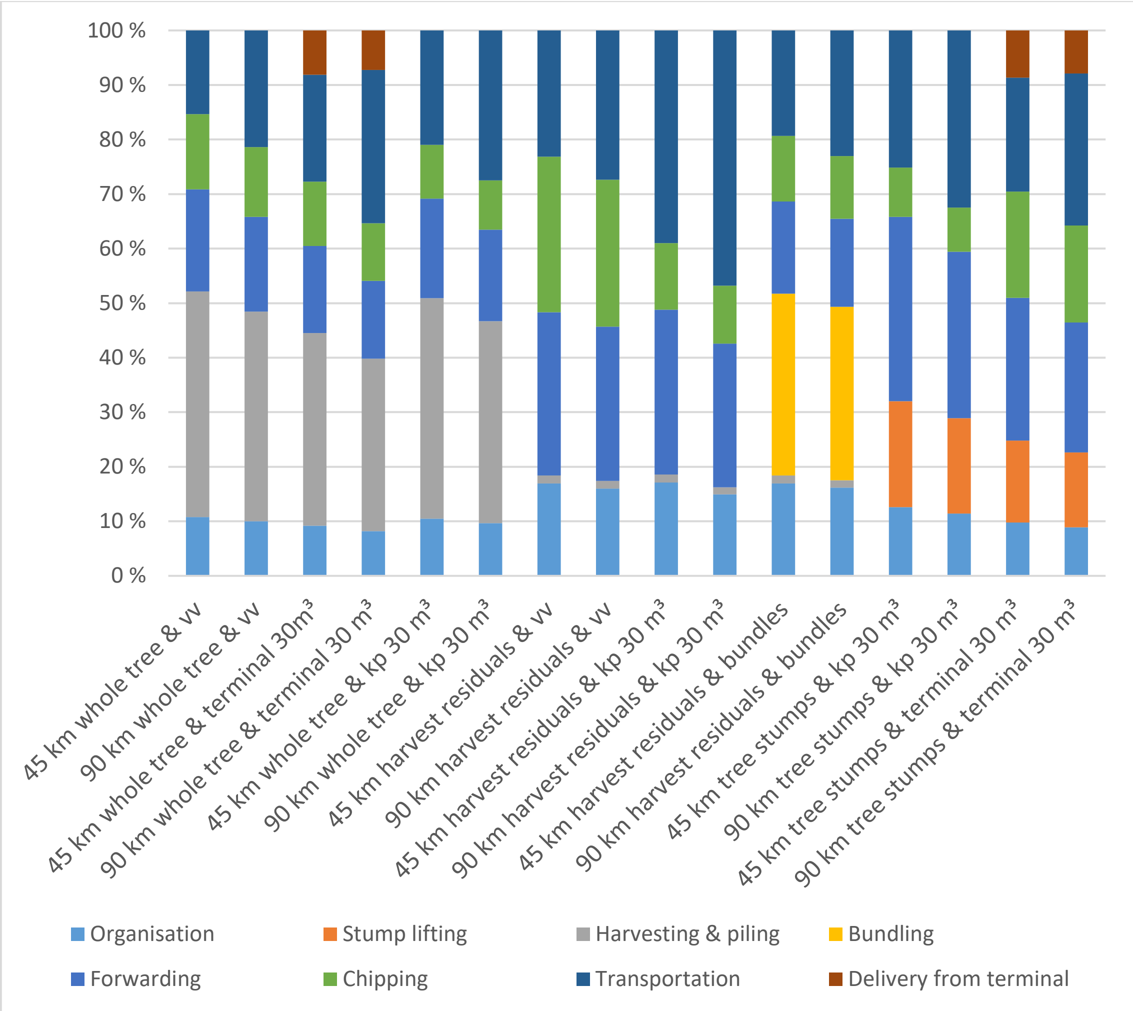

Figure 21. Relative cost structure of forest energy wood in Finland. (Source: Laitila *et al*. 2010)

6 MATERIALS AND METHODS

6.1 Simulation parameters

6.1.1 Data acquisition on simulation parameters

Data acquisition for the simulation parameters was conducted using pre-existing studies and research results. Data was gathered using search engines; Google scholar, Research gate, International journal of forestry research, Forest Science and Technology. The more case and supply chain type-specific parameters or values were provided by Asko Poikela (2019).

6.1.1 Vehicle parameters

The study is conducted as a simulation study by comparing existing or former HCT-vehicles from other studies or to a 25-meter-long vehicle. This was conducted by inspecting at their dimension's and weights. When conducting calculations as chip trucks, vehicles were assumed to have their announced tare weights and payload volumes. When calculating vehicles as loose biomass combination vehicles, 3.5 tonnes of weight were added to their tare weight and their maximum payload volume was reduced of 10 cubic meters of volume. This was conducted to simulate a crane with cabin, which weights up to 3.5 tonnes and takes up to 10 cubic meters of payload volume (Ammattilehti 2013). Every uncomminuted energy wood assortment was assumed to be chipped, to make cost calculations results comparable. Outline for the simulation is presented in figure 22.

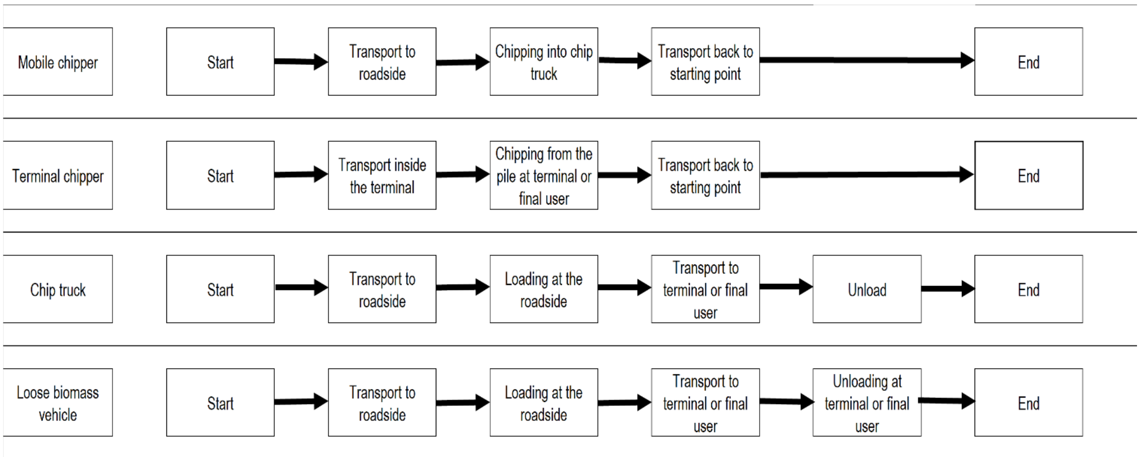

Figure 22. Simulation outline.

The travel distance on gravel forest roads was assumed to be 10 kilometers one way for the chip trucks and loose biomass vehicles. Mobile chipper was assumed to travel 20 kilometers and terminal chipper 5 kilometers for each load. Mobile chipper in this scenario is assumed to meet up with chip trucks, thus making it a hot supply chain.

Loading productivity for the chips trucks was assumed to be 120 cubic meters per hour (Laitila *et al*. 2016), due to the assumption of mobile chipper chipping straight into chip trucks cargo hull. Loose biomass vehicles were assumed to take up to 2.2 minutes per each tonnes loaded with harvest residuals (Lundberg 2016) and with delimbed stems 1.96 cubic meters in minute (Laitila & Väätäinen 2011).

Chip trucks were to unload their cargo, before delivery to be considered as done. Chips trucks unloading productivity were assumed to be 105.6 cubic meters of comminuted energy wood in an hour (Laitia & Väätäinen 2011). The unloading productivity with loose biomass vehicles to be 84 cubic meters per hour with delimbed stems and 129 cubic meters per hour for the loose residues (Heikkilä *et al*. 2005).

Chipping productivity was assumed to be 120 cubic meters per hour for both chippers (Poikela 2019) and terminal chipper was assumed to wait until loose biomass vehicles unload their cargo and then proceed to chip it from the pile.

6.1.2 TrailerWIN-parameters

The vehicle's turn ability was examined with TrailerWIN-program. Vehicles dimensions and axles placement were calculated from openly available pictures from online source using pixel calculations. Vehicles were assumed to have all of their axles down, to simulate their ability to steer when operating with a full payload. According to Finlex (2019) the test should be conducted the following way: "*…When the vehicle's out most tack is travelling on the 12.50 meter's circles radius and vehicles continuing straight forward, combination vehicle's inner side must not cross four-meter radius circle. No back tack is allowed to travel 0.8 meters towards the outer circle".* The test circle is presented in figure 23.

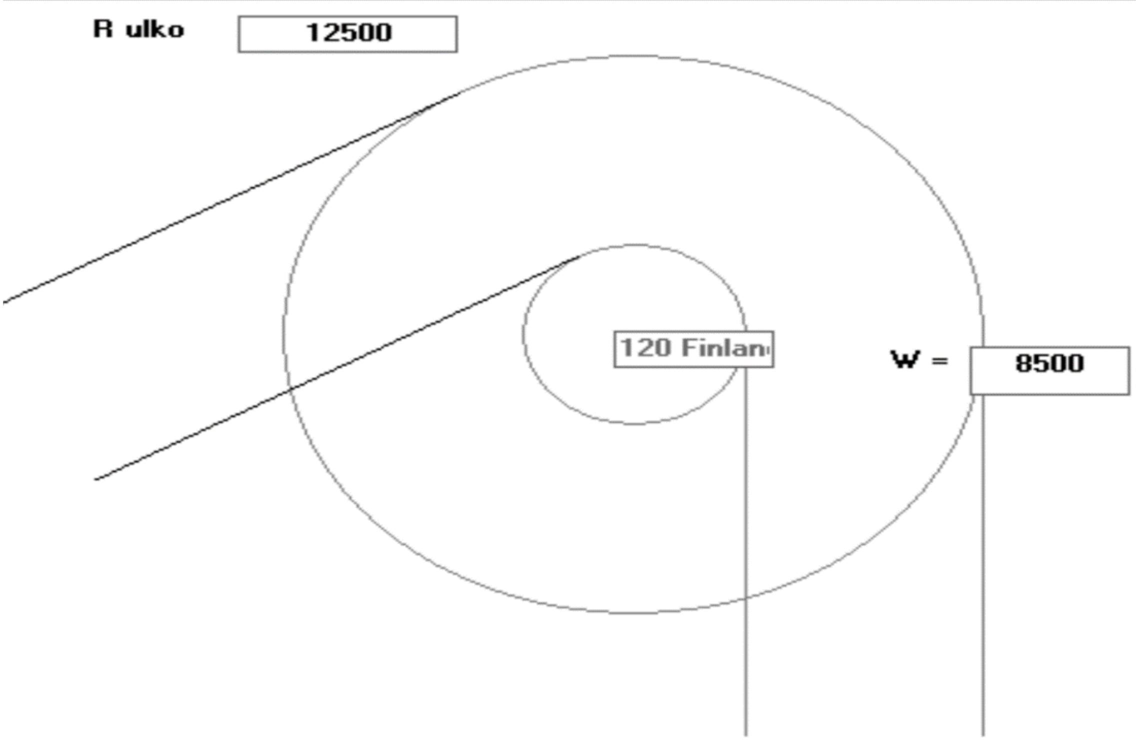

Figure 23. Finnish 120-degree turnability test. (Source: TrailerWIN 2019)

6.2 Simulated vehicles

6.2.1 30-meter HCT-vehicle

The ETT-vehicle (En trave till: one stack more) is from Swedish HCT-study to inspect longer and heavier vehicles in timber's long-distance transportation. The ETT-vehicle's tare weight was 28 tonnes, with a total length of 30-meters, with 180 cubic meters of cargo space, when operating as chip truck for loose biomass vehicle, corresponding values are 31.5 tonnes of tare weight and 170 cubic meters of cargo volume (Löfroth & Svenson 2012). The ETT-vehicle was chosen to be simulated due to its unique construct of modularity and multiple joints.

Figure 24. ETT-vehicle. Source: (Source: Trailer.se)

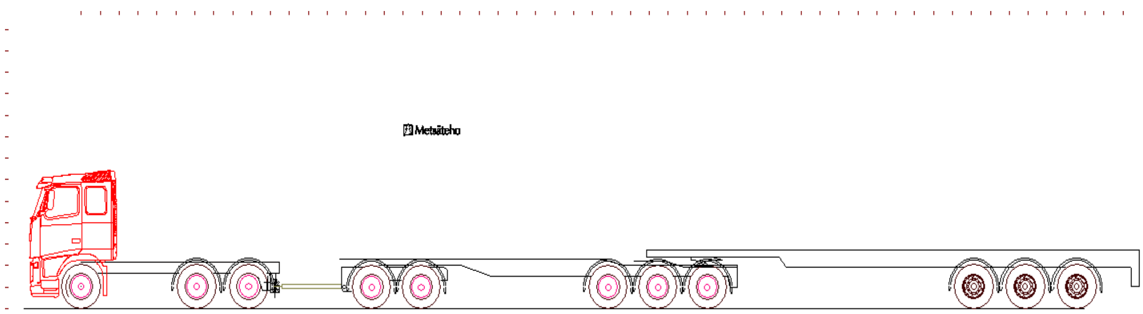

Figure 25. ETT-vehicle simulated in TrailerWIN-program

6.2.2 32-meter HCT-vehicle

DUO2-vehicle is also from a Swedish HCT experiment, where it was used to transport mixed goods. (Duo2.nu 2019). The vehicles tare weight is 32-tonnes, total length is 32 meters and cargo space is 200 cubic meters when operating as a chip truck in this simulation. As a loose biomass vehicle, corresponding values are: 35.5 tonnes of tare weight and cargo volume of 190 cubic meters. (duo2.nu 2019). The DUO2-vehicle was chosen for the study, due to its more common use and representation of an "average" HCT-vehicle on its length.

Figure 26. DUO2 HCT-vehicle. (Source: Koneporssi.fi)

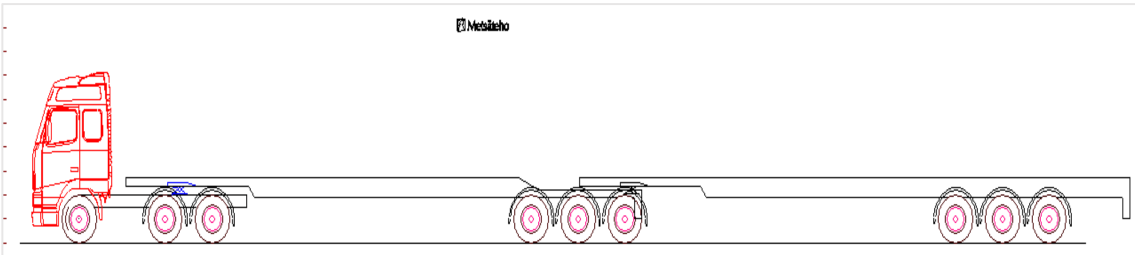

Figure 27. DUO2 as in simulated in TrailerWIN.

6.2.3 33-meter HCT-vehicle

The UPM's HCT-vehicle is from a Finnish HCT-experiment, where it transports wood chips between saw- and pulp mills. The UPM's HCT-vehicle is a constructed of a tractor, a semi-trailer and a full trailer. The tare weight is 33 tonnes, the total length 33 meters and load space 211 cubic meters when operating as chip truck. The corresponding values when operating as loose biomass vehicles are: tare weight of 36.5 tonnes and 201 cubic meters of cargo volume. (Hiltunen 2017). The vehicle was chosen to be included as the biggest possible option for the study.

Figure 28. UPM's HCT-vehicle. (Source: Metsäteho.fi)

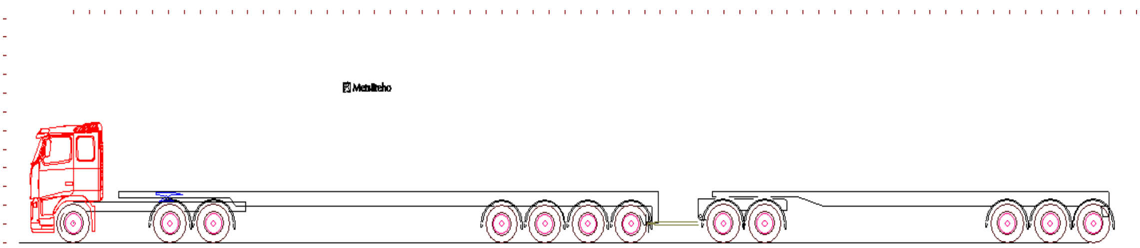

Figure 29. UPM as simulated in TrailerWIN-program

6.2.4 28-meter HCT-vehicle

Hakevuori's HCT-vehicle consists of a five axle truck and a five axle full trailer. Total combination length is 28-meters. Hakevuori is planned to be utilized both roadside and terminal wooden chip transport. Total combination length is 28-meters. (Metsäalan ammattilehti 2019). Due to unavailability of information on the trucks tare weight, I shall use "normal" vehicles' tare weight with an added 5 tonnes, making Hakevuori's tare weight to 30-tonnes and cargo space of 183 cubic meters when operating as chip trucks. Corresponding values as loose biomass vehicle are: tare weight 33.5-tonnes and cargo volume of 173 cubic meters. While operating from terminals, Hakevuori consists of a 13 meters truck and a 15 meters long full trailer and when operating from the roadside, five axle full trailer is changed to shorter three axle full trailer (Metsäalan ammattilehti 2019). In this simulation, Hakevuori is assumed to be operated at its 28-meter length.

Figure 30. Hakevuori's HCT-vehicle. (Source: Ammattilehti.fi)

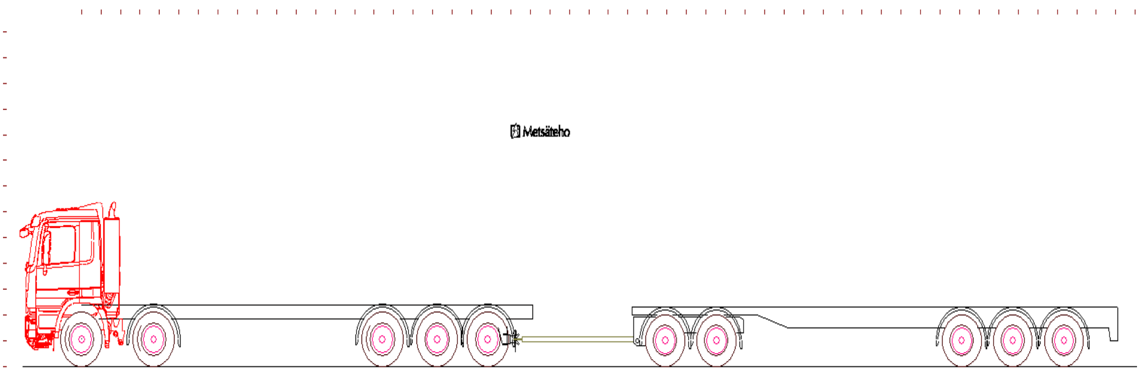

Figure 31. Hakevuori as simulated in TrailerWIN.

6.2.5 25.25-meters vehicle

A "normal" 25.25-meter-long vehicle was chosen as comparison. The normal vehicle consists of a truck and a full trailer. According to Venäläinen (2019) it is a vehicle with 30 tonnes of tare weight and 155 cubic meters of cargo space when operating as a chip truck and corresponding values as loose biomass vehicle are 33.5 tonnes of tare weight and 145 cubic meters of cargo volume.

Figure 32. “Normal” energy wood truck (Puuhuolto.fi)

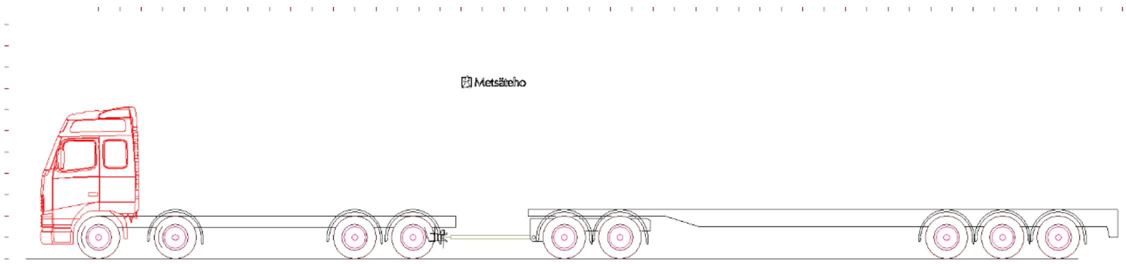

Figure 33. “Normal” energy wood truck simulated in TrailerWIN.

Table 8. Summary on simulated vehicle’s technical data as chip trucks.

Technical data	30-meter	32-meter	33-meter	28-meter	25.25-meter
Tare weight (tonnes)	28	32	33	30	30
Maximum (tonnes	76	76	76	76	76
Payload (tonnes)	48	44	43	46	46
Cargo volume (m3)	180	200	211	183	155

Table 9. Summary on simulated vehicle’s technical data as loose biomass vehicles.

Technical data	30-meter	32-meter	33-meter	28-meter	25.25-meter
Tare weight (tonnes)	31,5	35,5	36,5	33,5	33,5
Maximum (tonnes)	76	76	76	76	76
Payload (tonnes)	44,5	40,5	39,5	42,5	42,5
Cargo volume (m3)	170	190	201	173	145

6.4 Cost calculations for simulated vehicles

As the vehicles are not used in energy wood transportation or lack of suitable cost information, costs calculations can only be regarded as guidelines and generalizations. Formulas are based on Poikela's (2019) personal communications, Laitila & Väätäinen (2011) and Viitala et al. (2019) simulations and research. SKAL's (Finnish transport and logistics) cost calculation guidelines for transport companies were used to build up form (SKAL 2009). Table 10 presents the cost parameters for the different trucks when used for wood chip transportation. Table 11 does the same but for trucks equipped with a crane for use at forest landing.

Table 10. Normal and HCT-vehicles as chip trucks

	30-meter vehicle	32-meter vehicle	33-meter vehicle	28-meter vehicle	25.25-meter vehicle
Acquisition price, € (VAT 0 %)	390 000	390 000	400 000	385 000	250 000
Remaining value, € (VAT 0 %)	92549	92549	94922	91362	59326
Holding period, years	5	5	5	5	5
SOLID COSTS					
Depreciation, €/year	59490	59490	61016	58728	38135
Interest rate, €/year	7995	7995	8201	7893	5125
Insurance and governance €/year	10000	10000	10000	10000	10000
LABOUR COSTS					
Annual usage hours, h	2600	2600	2600	2600	2600
Annual working hours, h	2860	2860	2860	2860	2860
Utilization factor, %	60	60	60	60	60
Workers salary, €/h	14,68	14,68	14,68	14,68	14,68
Indirect salary costs, %	65	65	65	65	65
Annual labour costs together, €/a	69275	69275	69275	69275	69275
OPERATING COSTS					
Fuel price, €/litre (VAT 0 %)	1,036	1,036	1,036	1,036	1,036
Tires, re-surfacing, maintance, labour, €/a	110483	105491	112979	106163	100499
HOURLY COSTS					
When Idle, €/h (VAT 0%)	58	58	59	58	48
When driving unloaded, €/h (VAT 0%)	98	98	99	98	87
When driving loaded, €/h (VAT 0%)	105	105	106	105	94

Table 11. Normal and HCT-vehicles as loose biomass trucks.

	30-meter vehicle	32-meter vehicle	33-meter vehicle	28-meter vehicle	25.25-meter vehicle
Acquisition price, € (VAT 0 %)	465 000	465 000	475 000	460 000	325 000
Remaining value, € (VAT 0 %)	110347	110347	112720	109160	77124
Holding perioid, years	5	5	5	5	5
SOLID COSTS					
Depreciation, €/year	70931	70931	72456	70168	49575
Interest rate, €/year	9533	9533	9738	9431	6663
Insurance and governance €/year	10000	10000	10000	10000	10000
LABOUR COSTS					
Annual usage hours, h	2600	2600	2600	2600	2600
Annual working hours, h	2860	2860	2860	2860	2860
Utilization factor, %	60	60	60	60	60
Workers salary, €/h	14,68	14,68	14,68	14,68	14,68
Indirect salary costs, %	65	65	65	65	65
Annual labour costs together, €/a	69275	69275	69275	69275	69275
OPERATING COSTS					
Fuel price, €/litre (VAT 0 %)	1,036	1,036	1,036	1,036	1,036
Tires, re-surfacing, maintance, labour, €/a	110483	105491	112979	106163	100499
HOURLY COSTS					
When Idle, €/h (VAT 0%)	64	64	65	63	54
When driving unloaded, €/h (VAT 0%)	104	104	104	104	104
When driving loaded, €/h (VAT 0%)	111	111	111	111	111

6.5 Additional notes on normal and HCT-vehicles cost calculations.

6.5.1 Acquisition price

As HCT-vehicles do not exist as loose biomass or forest chips trucks, cost prices are estimations, which may affect greatly the hourly costs of the vehicles. The remaining values for tractors and trailers are calculated as 24 % of the acquisition value. The loan's interest rate was determined to be 1.84 % per year, according to Finnish banks average interest rate for enterprises. As entrepreneurs own required date of return was determined to be Finnish banks interest rate plus Poikela's (2019) recommended 1.5 %.

6.5.2 Fuel consumption

The fuel consumption and average travelling speed on highways and lower road junctions were set set to be equal for all vehicles. Fuel consumption was expected to be 50 liters per 100 kilometers while driving unloaded and 60 liters per 100 kilometers for driving loaded. As average speed, 60 kilometers per hour was used for time consumption on public and 20 km/h on forest roads (Laitila & Väätäinen 2011). This assumption is grave generalization as the amount of fuel consumption is heavily depended on the condition and hilliness of the roads, economical driving style, time of year and weight of the vehicle (Väkevä *et al*. 2004).

6.5.3 Insurance, maintance and management

The annual driving distance was assumed to be 200 000 kilometers and the assumption of "hot chain" were made. Tires were assumed to be 390 euros each and their lifespan to be 150 000 kilometers (Poikela 2019). Service was assumed to be 0.1 €/km for each distance transported and insurance was set to 10 000 euros annually (Viitala 2019; Poikela 2019).

6.6 Mobile and terminal chipper

6.6.1 Introduction to the chipper

One mobile chipper was chosen for both roadside and terminal chipping, as the same mobile chippers are often utilized both as roadside and terminal (Laitila & Väätäinen 2011). I decided to choose Mus-Max WT 11 mobile chipper, due to its capacity as mobile chipper and being able to chip whole trees, delimbed stems and harvest residuals (Mikkola 2018). The chipper's cost calculations as the terminal and as the mobile chipper are presented in table 12.

Figure 34. Mus-Max mobile chipper. (Source: konepörssi.fi)

Table 12. Mobile and terminal chippers cost calculations.

	Mobile chipper	Terminal chipper
Acquisition price, € (VAT 0 %)	773 000	773 000
Remaining value, € (VAT 0 %)	183437	103183
Holding period, years	5	7
SOLID COSTS		
Depreciation, €/year	117913	95688
Interest rate, €/year	8773	7119
Insurance and governance, €/year	36240	16320
LABOUR COSTS		
Annual usage hours, h	2600	2600
Annual machine hours, h	1690	2210
Utilization factor, %	65	85
Workers salary, €/h	13,24	13,24
Indirect salary costs, %	65	65
Annual labour costs together, €/a	2271984	2271984
OPERATING COSTS		
Fuel price, €/litre (VAT 0 %)	1,036	1,036
Tires, re-surfacing, maintance, €/a	36240	16320
Fuel consumption per comminuted l-m3, l	0,5	0,5
Productivity, l-m^3/h	120	120
HOURLY COSTS		
When driving, €/h (VAT 0%)	139	102
When chipping, €/h (VAT 0%)	151	105

6.6.2 Additional notes on the chippers

One of the most critical components of the chipper's hourly cost is utilization. Terminal chipper was determined to have a higher utilization rate, due to bigger amount of material to be comminuted. Thus, the annual distance travelled was set to be 50 % of the mobile chippers' value (Laitila & Väätäinen 2011; Poikela 2019). Due to the increased utilization level, terminal chipper was determined to have higher maintenance costs, 0.15 €/km and 0.20 €/km respectively, per annual kilometer travelled.

6.7 Energy wood properties

6.7.1 Simulated energy wood

In this study, I have decided to simulate two different kinds of energy wood, due to them being most common.

- Small diameter delimbed stems of pine, spruce and birch
- Harvest residuals with 100, 50 and 0 % of needles left

Small diameter energy wood was decided to be harvested as delimbed stems. Harvest residuals were assumed to consist of spruce's branches and to the different levels of needles was made to represent the drying process, where needles fall of the branches. As energy density, it was assumed 3600 MJ equals 1 MWh (Alakangas & Impola 2013). Characteristics are presented more closely in table 13.

Table 13. Energy wood's properties used in calculations

Source	Linndblad *et al.* 2013	Alakangas & Impola 2013
Variable Type	**Basic density, (kg/m^3)**	**Calorific value energy value, (Mj/kg)**
Spruce	400	19,02
Pine	385	19,33
Birch	475	19,15
Harvest residuals 100%	425	19,80
Harvest residuals 50%	445	19,75
Harvest residuals 0%	465	19,70

6.8 Energy content calculations

Energy wood's lower heating value is calculated with Alakangas & Impola's (2013) equation, when assuming waters density to be 1000 kg/m^3:

$$q_{p,net,ar} = q_{p,net,d} \times (100 - M_{ar}) \div 100 - 0.02443 \times M_{ar} \quad (1),$$

Where $q_{p,net,ar}$ is energy wood's lower heating value (MJ/kg). $q_{p,net,d}$ is energy wood's calorific energy value (MJ/kg) and M_{ar} energy wood's moisture content (%).

6.9 Vehicle's payload calculations

6.9.1 Payload volume and weight calculations

For the energy wood's bulk density at arrival state represents ability to load up the cargo space as full as possible is calculated with equation:

$$\rho_a = \left(\frac{\rho_{bd}}{(1-M_{ar})}\right) * Fg \quad (2),$$

Where ρ_a is energy woods bulk density at arrival state (kg/m^3). ρ_{bd} is energy woods basic density (kg/m^3). $M_{ar}$is energy woods moisture content (%) and Fg is fill grade (%).

A vehicle's maximum payload is limited by which are determined by the energy wood's bulk density at arrival state.

Calculation was conducted with Microsoft Excel program, using the following script:

$$m_{pw} = V_{mcs} \times \rho_a,$$

$$V_c = \frac{m_p}{\rho_a}$$

$$IF$$

$$m_{pw} > m_{mpw}$$

$$THEN$$

$m_{pw} = m_{mpw}$
$V_c = V_{mcs}$

Where m_{pw} is payload weight (kg). V_{mcs} is maximum payload volume (m^3). ρ_a is energy wood's bulk density at arrival state (kg/m^3). V_c is payloads volume (m^3) and m_p is payloads weight (kg).

Vehicles are loaded or chipped until the maximum payload volume is achieved. If vehicles maximum payload weight is smaller than fully loaded or chipped vehicles payload weight, the vehicle is assumed to be loaded or chipped to the maximum payload weight.

6.9.2 Payload energy content

The Payload's energy content is calculated using the following equation (Alakangas & Impola 2013):

$$q_p = \frac{q_{p,net,ar} \times m_{pw}}{3600} \qquad (3),$$

q_p is the payloads energy content at arrival state (MWh), $q_{p,net,ar}$ is payloads energy woods lower heating value at arrival state (MJ/kg). m_{pw} is the payloads weight (kg) and when assuming one MWh equals 3600 MJ.

6.10 Cost calculations

6.10.1 Loading and unloading

The following equation was used to calculate loading and unloading costs for the chip trucks or loose biomass vehicles:

$$C_{lu} = \frac{V_c}{P_{lu}} \times C_i \qquad (4),$$

Where $C_{lu}$is costs (€) for the payload caused by the loading or unloading, V_c is the payloads volume (m^3), P_{lu} is productivy of loading or unloading and C_i is the hourly cost (€/h) for the idle chip truck or loose biomass vehicle.

6.10.2 Chipping costs

The following equation was used to calculate loading and unloading costs for the chip trucks or loose biomass vehicles:

$$C_c = \frac{V_c}{P_c} \times C_i \qquad (5),$$

Where $C_c$is costs (€) for the payload caused by the chipping at the forest landing or at the , V_c is payloads volume (m^3), P_c is productivity of mobile or terminal chipper and C_i is hourly cost (€/h) for the idle chip truck or loose biomass vehicle.

6.10.3 Long distance transport costs

Long distance transport distance consists of travel on public road, then on a gravel road to the forest landing then back the same route. The distance from public road to forest landing is assumed to be 10 kilometers in all cases and the speed to be 20 km/h. On public road the speed is assumed to be 60 km/h. The total cost for the one load is calculated using the following equation:

$$C_{ld} = C_e(\frac{10}{20} + \frac{d}{60}) + C_f(\frac{10}{20} + \frac{d}{60}) \qquad (6),$$

Where $C_{ld}$is the cost of long distance transport (€), $C_e$is chip trucks or loose biomass vehicles hourly operating costs when driving empty and d is distance (km) on public road and C_f is hourly operating cost (€/h) when operating fully loaded.

6.10.4 Total costs for the payload

Total costs for the payload can be calculated using the following equation:

$$C_{tot} = \frac{C_{ld} + C_c + C_{lu}}{q_p} \quad (7),$$

Where C_{tot} is total costs for the payload (€/MWh), $C_{ld}$is the cost of long-distance transport (€), $C_c$is cost (€) for the chipping. C_{lu} is costs (€) for the payload caused by the loading and unloading. $q_p$is the payloads energy content (MWh).

6.11 Simulated scenarios

6.11.1 Normal simulated scenario

The first simulated scenario is called the normal scenario. Moisture content was set out to be 50 % for all of the energy wood. Recently harvested energy wood's moisture content can be assumed to differ between 40–50 %. Fill grade was set to be 20 % for the uncomminuted energy wood and for comminuted corresponding value was 40 % (Ranta & Rinne 2006; Laitila & Väätäinen 2011). Energy content (MJ/kg) was calculated using equation 3. Summary of energy woods properties in the "normal" scenario are presented in table 15.

Table 15. Energy woods characteristics used in normal scenario. U = uncomminuted; C = Comminuted

Species	Spruce		Pine		Birch		Harvest residuals 100 %		Harvest residuals 50 %		Harvest residuals 0 %	
Characteristic	*U*	C	*U*	C	*U*	C	*U*	C	*U*	C	*U*	C
Frame density (%)	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00
Moisture content (%)	50	50	50	50	50	50	50	50	50	50	50	50
Lower calorific heating value (Mj/kg)	8,29		8,44		8,35		8,68		8,65		8,63	

6.11.2 Dry simulated scenario

The second scenario was set out to simulate the “dry” scenario. In the dry scenario, energy wood has been drying at the forest landing for an extended period of time or has been dried up, thus decreasing moisture content. Moisture content for all of the energy wood types was set out to be 20 %. Fill grades were set to be same as normal scenario, 20 % for uncomminuted and 40 % for the comminuted. Energy content (MJ/kg) was calculated using equation 3. Summary of energy wood values used on dry scenario is presented in table 16.

Table 16. Energy woods characteristics used in dry scenario U = uncomminuted; C = Comminuted

Species	**Spruce**		**Pine**		**Birch**		**Harvest residuals 100 %**		**Harvest residuals 50 %**		**Harvest residuals 0 %**	
Characteristic	*U*	C	*U*	C	*U*	C	*U*	C	*U*	C	*U*	C
Frame density (%)	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00	20,00	40,00
Moisture content (%)	20	20	20	20	20	20	20	20	20	20	20	20
Lower calorific heating value (Mj/kg)	14,73		14,98		14,83		15,35		15,31		15,27	

7 RESULTS

7.1 Normal simulated scenario with comminuted energy wood

7.1.1 Usage of cargo space and gross weight with comminuted energy wood under normal scenario

When comparing HCT-vehicles' and normal 25.25-meter long vehicles' performance in long-distance transportation of comminuted energy wood under normal scenario increased cargo space does not seem to be necessary. All of the simulated vehicles hit their maximum gross weight before reaching the limit on their maximum cargo volume. With comminuted delimbed stems, HCT-vehicles reach their maximum gross weight leaving between 24.3 and 97.8 cubic meters of cargo space unused. While normal 25.25-meter vehicle leaves between 5.6 to 33.9 cubic meters of cargo space unused.

When inspecting used gross weight and cargo space with comminuted harvest residuals, HCT-vehicles compare a little better than with delimbed stems. HCT-vehicles leave 38.8 and 95.4 cubic meters of cargo unused. Normal 25.25-meter vehicle leaves 19.7 and 31.3 cubic meters of cargo space unused. Usages of cargo spaces and payloads weights are presented in detail the appendix 1.

7.1.2 Absolute and relative costs with comminuted energy wood under normal scenario

When comparing absolute and relative long-distance transport costs when transporting comminuted energy wood, HCT- vehicles seem to be an inferior option than the regular 25.25-meter vehicle. The costs per transported MWh are on average at short distances is 0.1 € cheaper or slightly more expensive when using the 25.25-meter vehicle. With longer transport distances difference grows. HCT-vehicle are up to 1 € more expensive per transported MWh on longer distances than the 25.25-meter vehicle. The relative costs difference is between -1 - 15 % more expensive. The results for the delimbed spruce are in figure number 35 and 36. The Results for the comminuted pine, birch and harvest residuals are presented in the appendix 2.

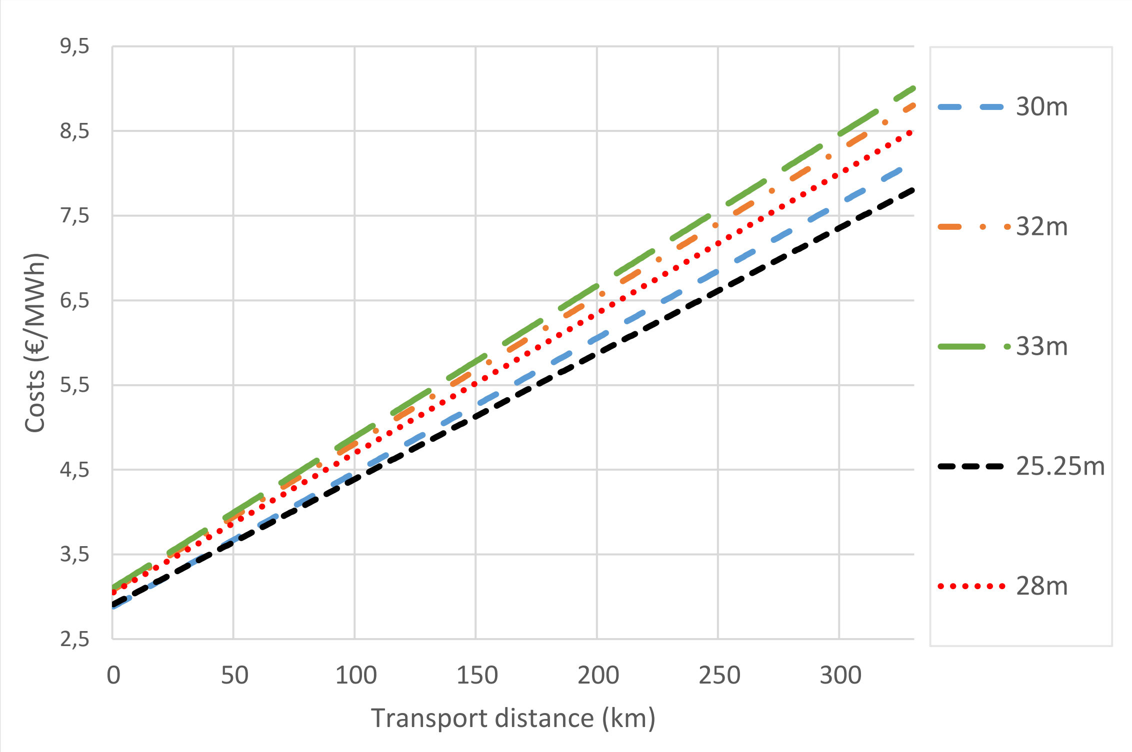

Figure 35. Absolute costs, € per MWh when transporting comminuted spruce under normal scenario

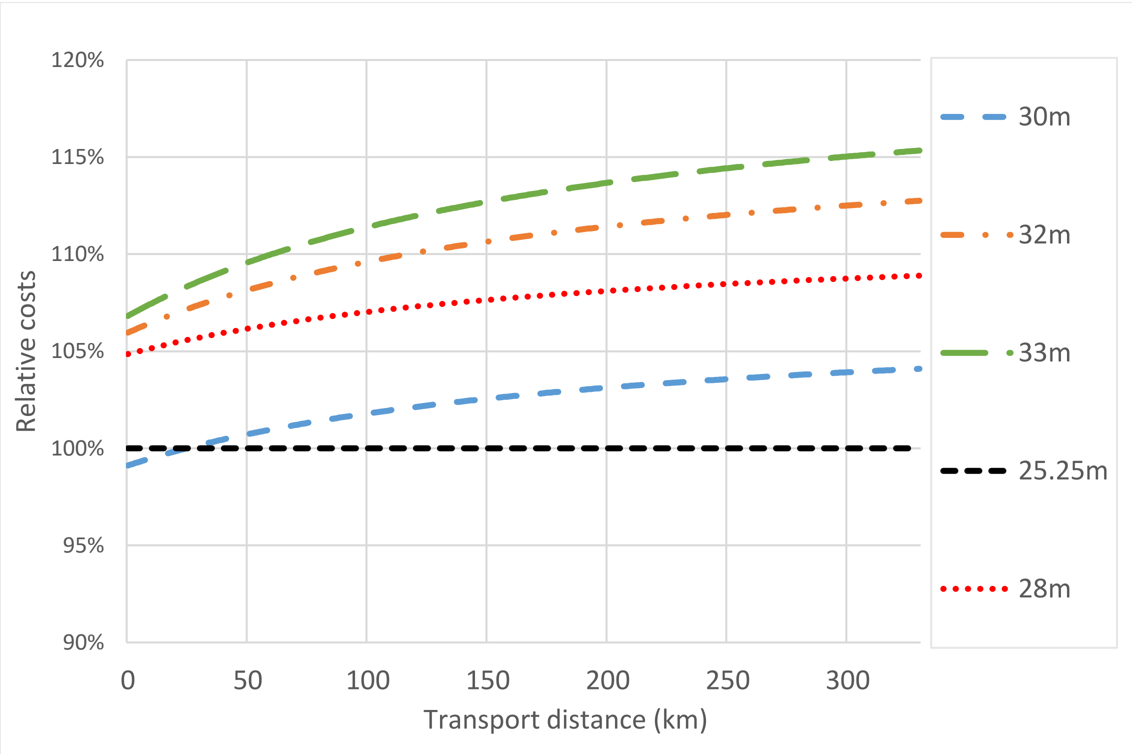

Figure 36. Relative costs per MWh when transporting comminuted spruce comparing to normal 25.25-vehicle under normal scenario

7.2 Normal simulated scenario with uncomminuted energy wood

7.2.1 Usage of cargo space and gross weight with uncomminuted energy wood under normal scenario

When comparing HCT-vehicles and the normal 25.25-meter long vehicle performance in long-distance transportation of uncomminuted energy wood under the normal scenario, increased cargo space seems to be justifiable. None of the simulated vehicles reaches their maximum gross weight before filling up their cargo space. On the contrary, all the vehicles leave between 1.3 and 20-tonnes of their maximum gross weight unused with delimbed energy wood stems. With harvest residuals, corresponding values are between 2.1 and 17.8 tonnes of weight. Results with used cargo space and payload weights are presented in appendix 1.

7.2.2 Absolute and relative costs with uncomminuted energy wood under normal scenario

When comparing absolute and relative costs when transporting uncomminuted energy wood, HCT-vehicles outperform normal 25.25-meter-long vehicle. HCT-vehicles start as more expensive than the normal 25.25-meter vehicle, between 1 and 0.5 euros per transported MWh. Break-even occurs between 31 and 148 kilometers of distance travelled. HCT-vehicles are up to 15 % cheaper than normal 25.25-meter-long vehicle. Results for uncomminuted harvest residuals at 50 % of needles left are presented in figures number 37 and 38. Results for the uncomminuted spruce, pine, birch and rest of the harvest residuals are presented in appendix 3.

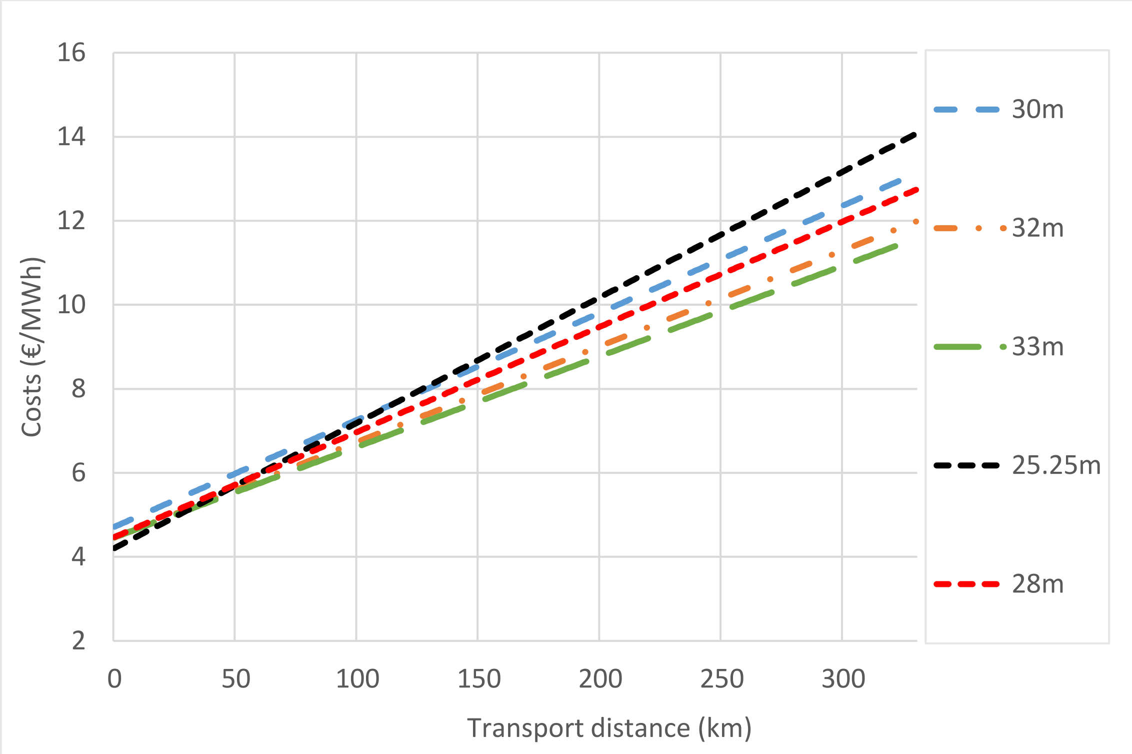

Figure 37. Absolute costs, € per MWH when transporting harvest residuals at 50 % of needles left under normal scenario.

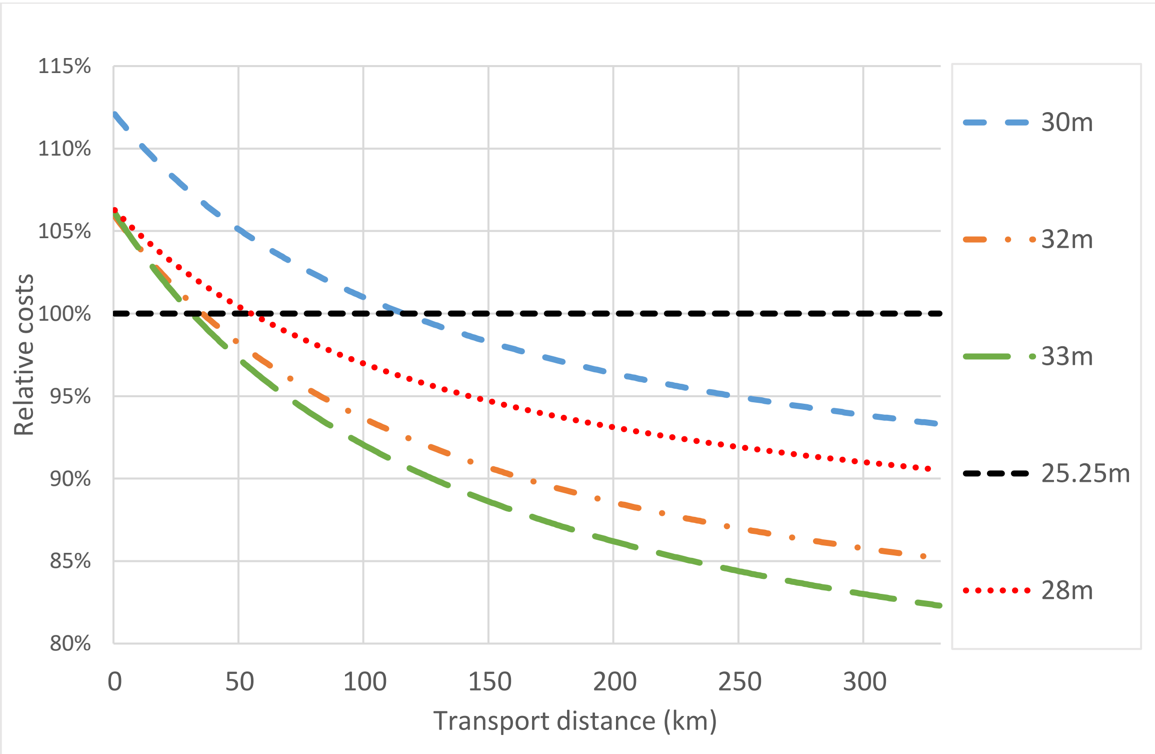

Figure 38. Relative costs per MWh when transporting uncomminuted harvest residuals with 50 % of needles left comparing to normal 25.25-vehicle under normal scenario.

7.3 Dry simulated scenario with comminuted energy wood

7.3.1 Usage of cargo space and gross weight with comminuted energy wood under dry scenario

When comparing differences between simulated vehicles under the “dry” scenario, cargo space gets filled more efficiently. Only 32- and 33-meter HCT-vehicles leave cargo space unused. Unused cargo space varies between 2.2 and 29.9 cubic meters. Unused gross weight is bigger than normal scenario between 0.8 and 21 tonnes. HCT-vehicles seem to have benefitted from decreased moisture content when comparing of used cargo space and gross weight. The usage of cargo space and payload weights are presented in appendix 4.

7.3.2 Absolute and relative costs with comminuted energy wood under dry scenario

When transporting extremely dry comminuted energy wood HCT-vehicles compare better than in the normal scenario. Absolute costs start at the same levels with all of the simulated vehicles expect the 30-meter long HCT-vehicle which is 0.5 € cheaper per transported MWh than the regular vehicle at the start of long-distance transport. Relative costs start at 2 % more expensive than the normal 25.25-meter vehicle change to 12 % less expensive. Break-evens occur between 14 and 72 kilometers. The results for the absolute and relative costs for comminuted spruce are presented in figures 26 and 27.

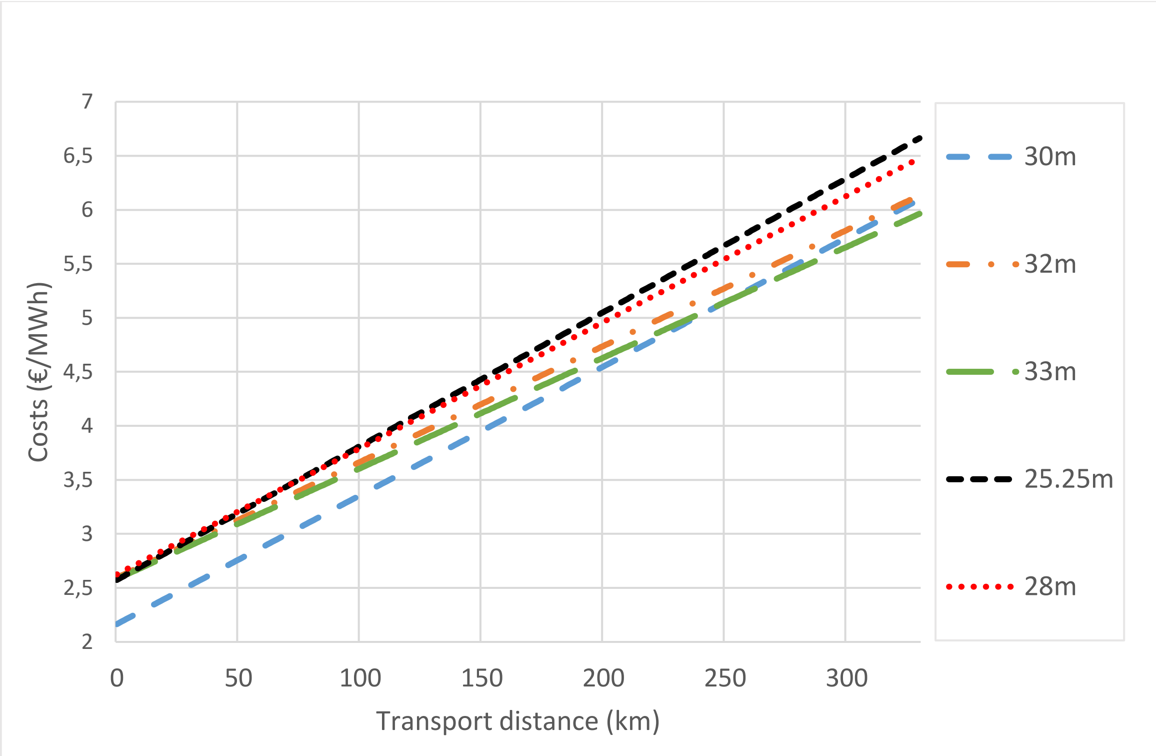

Figure 39. Absolute costs, € per MWh when transporting comminuted spruce under dry scenario.

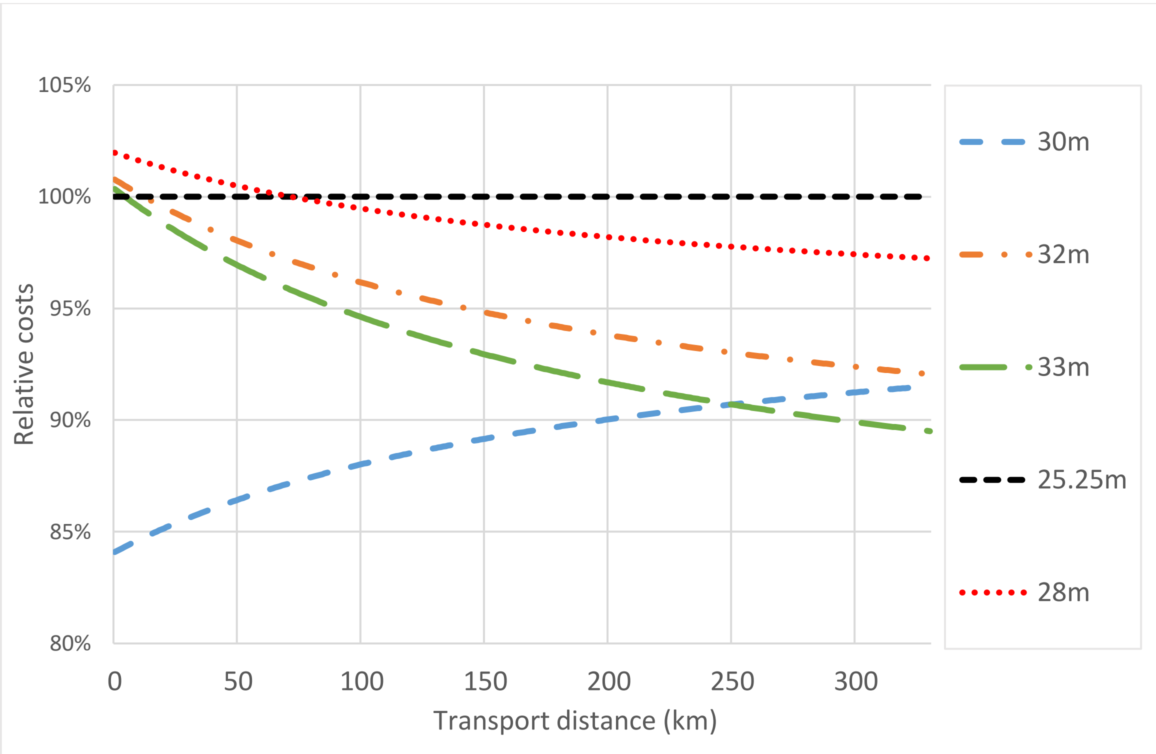

Figure 40. Relative costs per MWh when transporting comminuted spruce when comparing to normal 25.25-vehicle under dry scenario.

7.3.3 Usage of cargo space and gross weight with uncomminuted energy wood under dry scenario

When comparing the usage of cargo space with uncomminuted energy wood, all the simulated vehicles use all of the cargo space with all energy wood types and leave part a part of the maximum gross weight unused. Unused maximum gross weight varies between 28 and 15 tonnes, with the 25.25-meter using the least and the 33-meter using the most.

7.3.4 Absolute and relative costs with uncomminuted energy wood under dry scenario

At short distances the normal 25.25-meter vehicle is up to 0.5 € less expensive per transported MWh than all the HCT-vehicles on short distances. On longer distances HCT-vehicles are up to 2 € less expensive per transported MWh than the normal 25.25-meter vehicle. Break-evens occur between 23 and 190 kilometers of transport distance. Relative costs are between 5 and 15 percent cheaper than normal 25.25-meter vehicle after the break-evens. Absolute and relative costs are presented in graphs 28 and 29.

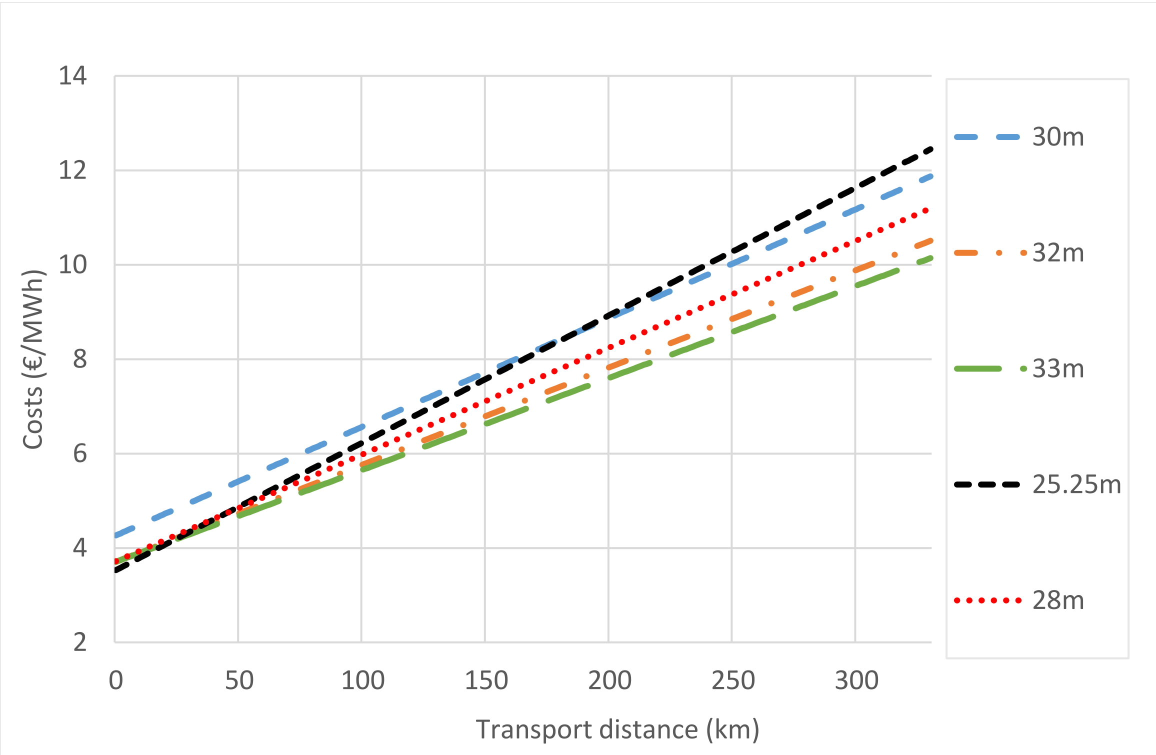

Figure 41. Absolute costs, € per MWh when transporting uncomminuted harvest residuals at 50 % of needles left under dry scenario.

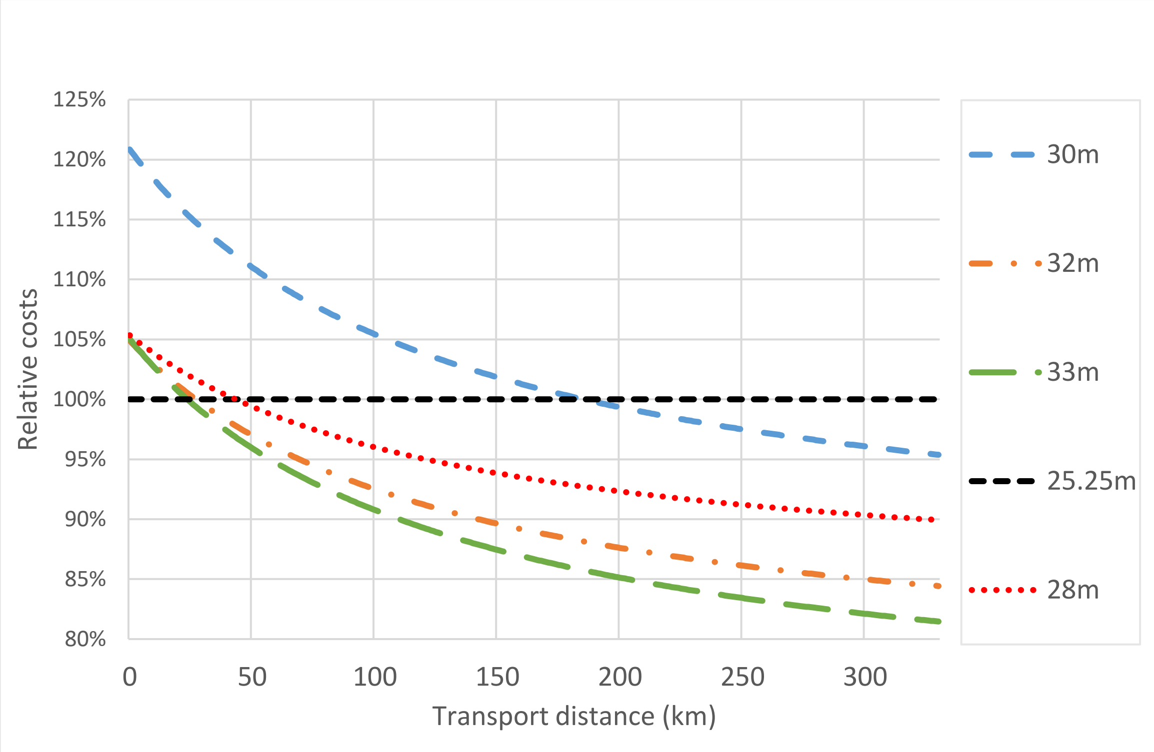

Figure 42. Relative costs per MWh when transporting uncomminuted harvest residuals at 50 % of needles left when comparing to normal 25.25-vehicle under dry scenario.

7.4 Summary of absolute costs under the normal scenario

Under the normal scenario, HCT-vehicles performance varies with different energy wood when compared to the normal 25.25-meter vehicle. For transport distances between 1 and 330 kilometers, HCT vehicles are 0.45 euros more expensive per transported MWh than the normal vehicle when transporting comminuted energy wood. For uncomminuted energy wood, HCT-vehicles outperform the normal vehicle. HCT-vehicles are 0.5 euros less expensive per transported MWh than the normal vehicle.

7.5 Summary on absolute costs under dry scenario

Under the dry scenario, HCT-vehicles perform better than in the normal scenario. Transport distances between 1 and 330 kilometers, HCT-vehicles are up to 0.5 euros less expensive per transported MWh than the normal 25.25-vehicle. HCT-vehicles are more cost-efficient after 49 kilometers of travel when delivering comminuted energy wood. With uncomminuted energy wood, HCT-vehicles are on average 0.45 more cost-efficient per delivered MWh than regular vehicle. HCT-vehicles are on average more cost efficient after 79 kilometers of transportation.

7.6 TrailerWIN-tests

7.6.1 Normal 25.25-meter normal vehicles maneuverability test

Results for the normal 25.25-meter vehicle is presented in figure 30.

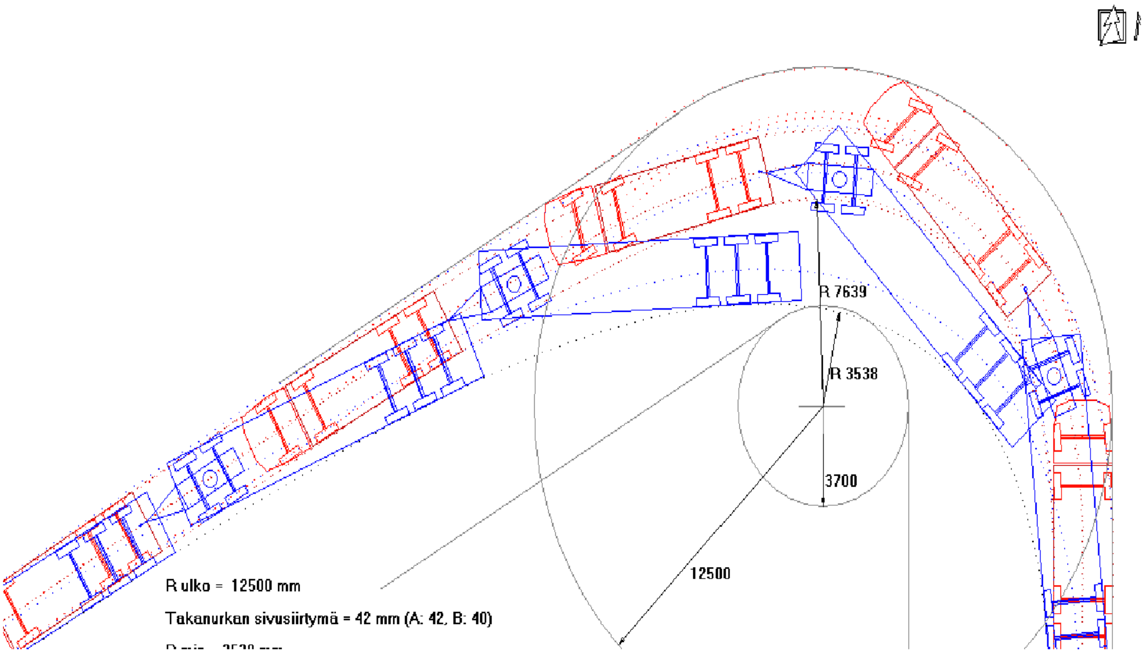

Figure 43. Normal 25.25-meter vehicle's 120-degree maneuverability test.

From the figure 30, It is possible to see a minor cut on the inner test circle: 172 millimeters. This cut on the inner circle could be considered as minor and due to possible mistakes in TrailerWIN-program, the normal vehicle could be said to pass the test.

7.6.2 30- meter long HCT-vehicle maneuverability test

In the figure 31, is 30-meter long HCT-vehicles simulated 120-degree maneuverability test.

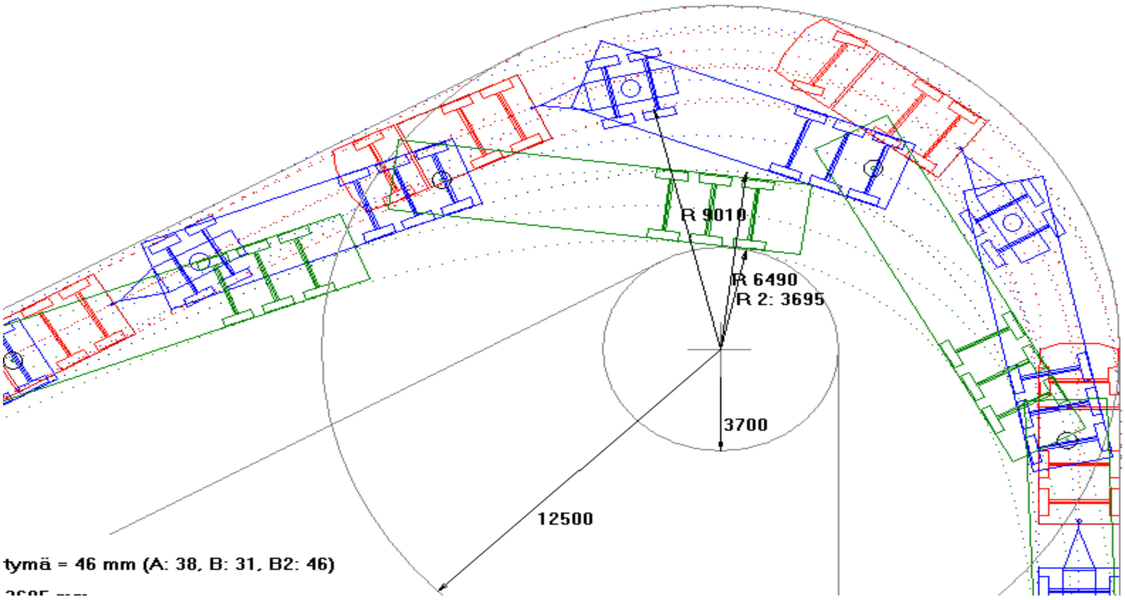

Figure 44. 30-meter vehicles maneuverability test

30-meter long HCT-vehicle cuts the inner circle by 5 millimeters, and when accounting the possible mistakes in TrailerWIN-program, the 30-meter long vehicle could be said to pass the test. This is due to 30-meter HCT-vehicles multiple joints and shorter trailers, which allows it to maneuver more easily on corners and turnabouts.

7.6.2 28- meter long HCT maneuverability test

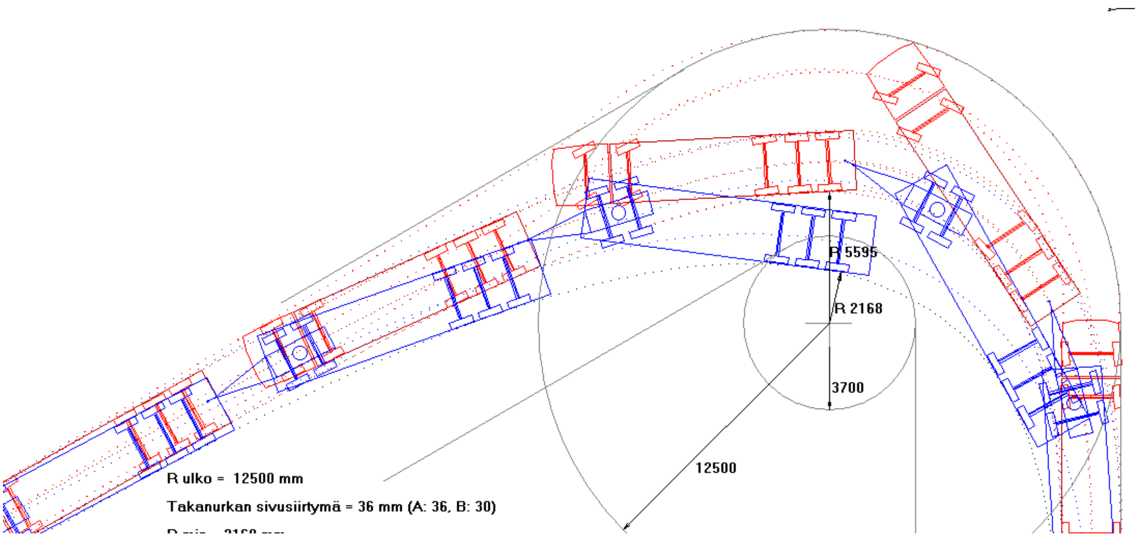

Figure 45. 28-meter long HCT-vehicle maneuverability test

When inspecting Hakevuori's 28-meter long HCT-vehicles maneuverability test we can observe clear failure on the maneuverability test by 1532 millimeters. This is due to Hakevuori's HCT-vehicles construct: a long truck and a long trailer. Clear failure in maneuverability test could limit severely usage on harder to access forest roads but the Trailer-WIN-program is unable to simulate steering back bogie, thus making the test unreliable. It is important to note that Hakevuori's HCT-vehicle is not designed to operate on forest roads as 28-meter HCT-vehicle.

7.6.3 32-meter long HCT-vehicles maneuverability test

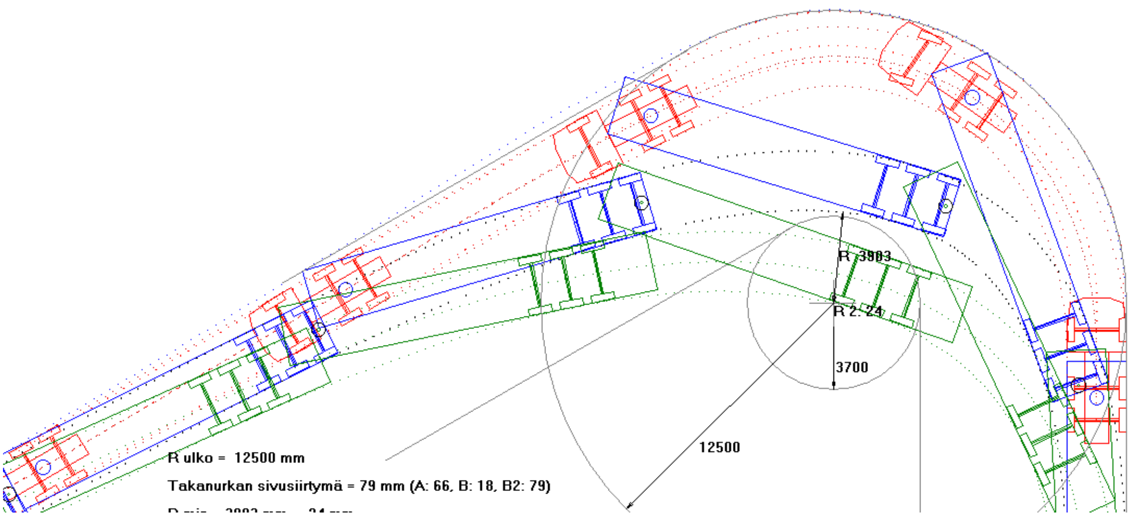

Figure 46. 32-meter long HCT-vehicle maneuverability test

When inspecting 32-meter HCT-vehicles maneuverability test, we can clearly observe failure; the last semi-trailer cuts the inner circle by 3676 millimeters. 32-meter HCT-vehicle constructs rely on B-link trailer, which has great combability but bad maneuverability. However, 32-meter HCT-vehicle is not designed to operate on forest roads. 32-meter HCT-vehicle is the on the longer side on the simulated vehicles and has a reputation on being hard to maneuver on tight turnabouts and forest roads.

7.6.4 33-meter long HCT-vehicles maneuverability test

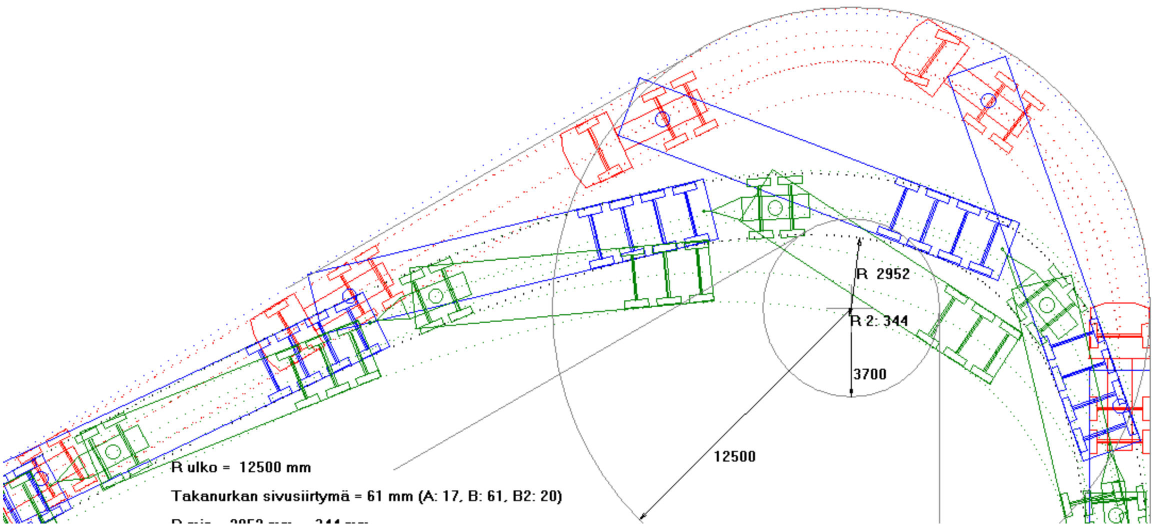

Figure 47. 33-meter long HCT-vehicle maneuverability test

When inspecting UPM’s maneuverability test, we can clearly observe UPMS’s 33-meter-long vehicles failure: the last semi-trailer cuts the inner circle by 3356 millimeters. UPM is the on the longest of the simulated vehicles, and its construct of tractor, dolly and two semi-trailers aid the UPM’s on tight corners.

7.7 Summary on maneuverability tests

When examining the performance of HCT-vehicles on Finnish’s 120-degree maneuverability test, all the vehicles struggle to pass it. Normal and 30-meter HCT-vehicle can be argued to pass it, but other HCT-vehicles fail it with clear marginal. Construct and length could be the reason behind the different results. 30-meter HCT-vehicles construct of three trailers and 33-meter HCT-vehicles dolly-trailer seems to enable better maneuverability.

Normal vehicles shorter length helps, when last trailer does not have possibility to cut the corner. It is important to note, that vehicles were assumed not to have turning axles. Results for the maneuverability tests are presented in table 17.

Table 17. Maneuverability test results.

Vehicle	Cut of inner circle (mm)	Test result
25.25-meter normal	162	Pass
30-meter HCT	5	Pass
28-meter HCT*	1532	Failure *but no steerable back bogie
32-meter HCT	3676	Clear failure
33-meter HCT	3356	Clear failure

8 DISCUSSION

8.1 Cost simulation

8.1.1 Vehicles running costs

When simulating HCT-vehicles for energy woods long distances transportation, it is important to note the uncertainty of the used parameters. HCT-vehicles in energy wood transportation does not exist on large scale at the moment. Thus all of the used parameters for fixed costs can be regarded as “guide lines” rather than “absolute” truths. This is due to the rarity of HCT-vehicles and as all currently operating HCT-vehicles in Finnish forestry fields are utilized for terminal based operations and timber or wood chips transportation, no clear picture can be drawn about the vehicles running costs. When the operating HCT-fleet in forestry has grown in numbers, more accurate data can be obtained.

8.1.2 Time consumption

The average time consumption on forest- and public roads is depending on road and weather conditions, including the skill of the driver. A vehicle’s maneuverability impact on time consumption is challenging to include in the simulation, due to lack of existing HCT-vehicle’s operating on forest roads. Due to this, vehicle’s speed on roads were assumed to be equal for all vehicles. It is unclear, if over 25.25-meter vehicles will ever be able to operate on forest roads at large scale and if they can be operated, how much time consumption will increase. Until more experiment-based research is conducted, the time consumption remains uncertain.

8.1.3 Loading and unloading

When considering loading and unloading vehicles, set up and tear down times were assumed to be zero. This was due to the inability to determinate fixed values for loading the uncomminuted energy wood in extra-long and large HCT-vehicle. Loading energy wood is heavily depended on driver’s skill and the used equipment. HCT-vehicle’s increased length may cause unexpected problems, increasing time consumption significantly or making loading the vehicle up to maximum payload impossible. At the moment of writing this thesis, no crane manufacturer offers cranes with big enough reach to conveniently load over 25.25-meter-long vehicle.

8.1.4 Payload

In the calculations payload weight and size was determined by the moisture content, fill grade and available cargo space. The used equations for the energy wood's density and energy content can be regarded relatively accurate. This due characteristic being the standard values. Fill grade is affected heavily by driver's skill level on loading and available tools for compacting the load, mainly with uncomminuted energy wood. Used values for the simulation can be held as guidelines and generalizations.

The simulated vehicles tare weights, especially for loose biomass are affecting heavily on the results. The used values for the crane with cabins were chosen to be on the upper limits, due to possibility of need of longer and heavier crane. The 30-meter HCT-vehicles low tare weight can be regarded as a generalization.

8.1.5 TrailerWIN simulations

It is important to notice that TrailerWIN calculations only give some picture on simulated vehicles maneuverability. Pixel calculations might give wrong measurements for the vehicles, thus throwing off the simulation. It is important that 30-meter and 32-meter-long HCT-vehicles originate from Sweden, which have different maneuverability criterias for HCT-vehicles. They are not designed to operate outside the preplanned routes, thus failure on the maneuverability is to be expected.

8.1.6 Simulated scenarios

The simulated scenarios were chosen to present the most common situation and extremely low moisture content scenario. In practice moisture content of 20 % is hard to achieve when drying energy wood at forest landings or at wood lots. Thus, the dry scenario represents transporting comminuted energy wood or wood chips from sawmills and pulp mills.

8.2 Results on normal scenario

8.2.1 Comminuted energy wood normal scenario

The results for the normal, moisture content of 50 %, scenario on the comminuted energy wood are as the hypothesis predicted. Due to increased tare weight, all the extra cargo space could not be utilized. Thus, making longer HCT-vehicles impractical to use. All the HCT-vehicles were on average more expensive to operate, but the 28-meter long HCT-vehicle performed best when compared to normal 25.25-meter. Even with 28-meter long HCT-vehicle, the break-even point was at 14 kilometers, which makes operating HCT-vehicle with 76-tonnes maximum gross weight redundant in those conditions.

8.2.1 Uncomminuted energy wood normal scenario

The results for the uncomminuted energy wood follow the hypothesis. Transport of uncomminuted energy wood with HCT-vehicles is more feasible than of comminuted energy wood. All of the HCT-vehicles performed better than the normal 25.25-meter vehicle and savings were substantial. HCT-vehicles were more expensive to operate on shorter distances but break-even occurs on average after 79 kilometers of transportation.

It is important to notice, that uncomminuted energy wood is not transported over long distances. According Official Statistics of Finland (2020), between 2016 and 2018 average transport for uncomminuted energy wood was 64 kilometers. With this knowledge, HCT-vehicles may not bring substantial change in the supply chain as they offer an economical option for longer distances.

8.3 Results on dry scenario

8.3.1 Comminuted energy wood under dry scenario

Under the dry scenario results for the comminuted energy wood change considerably. HCT-vehicles are more cost efficient than normal 25.25-meter vehicle, the difference being 0.24 € per delivered MWh on distances over 330 kilometers. Break-even occurs at 49 kilometers transport distance. Under this simulation, when comparing Official Statistics of Finland (2020), between 2016 and 2018 average comminuted wood transport distance was 108 kilometers, thus utilizing HCT-vehicles would be feasible.

However, energy wood reaching the extremely low moisture content of 20 % is very unlikely to occur after drying at forest landing. Moisture content for dry wooden chips from sawmills or energy wood terminals could reach lower moisture content levels.

8.3.2 Uncomminuted energy wood under dry scenario

Results do not differ much from normal scenario with uncomminuted energy wood, due to maximum gross weight not being the limiting factor. HCT-vehicles are on average 0.45 € cheaper per delivered MWh than normal 25.25-meter vehicle and break-even occurs at the same 79 kilometers of travel.

8.4 Future of the HCT-vehicles

8.4.1 Future research topics

The use of HCT-vehicles on forest roads is one of the most challenging part of this study. Due to their increased maximum length and number of axles, the design of forest roads might not be able to support the utilization of HCT-vehicles. Thus, field experiments on the maneuverability on forest roads, most suitable construct of HCT-vehicle and required auxiliary technology need to be evaluated more.

8.4.2 Future of the HCT-vehicles and vehicles dimensions and laws

The currently maximum gross weight of the vehicles in Finland is 76 tonnes and maximum length is 34.5 meter. When inspecting the evolution of Finnish vehicle laws and the experiences with over 76 tonnes vehicles, an increase of the maximum gross weight is to be expected. However, at the moment of writing this thesis, Traficom has no projects currently running to increase the maximum gross weight.

8.4.3 Future of the HCT-vehicles in Finnish transportation industry

Finnish transport companies have accepted the chance to operate HCT-vehicles with open arms. Currently there are over 300 HCT-vehicles operating in Finland (Hämeen Sanomat 2020). Thus if the maximum gross weight of the vehicles increases the number of HCT-vehicles can be expected to rise.

Within forestry industry and transportation of timber straight transport operations can be expected to decrease. In the future straight transportations of timber or energy wood will be replaced by terminal based actions due to troublesome operation of HCT-vehicles on forest roads. The most probable scenario is to utilize normal length and weight vehicles on lower road network and HCT-vehicles on such called HCT-fairways.

9 CONCLUSIONS

When utilizing HCT-vehicles with maximum gross weight of 76 tonnes and length over 25.25 meters in energy wood's long-distance transportation, transporting uncomminuted energy wood is economically a better option than the normal vehicle. With all compared energy wood types, HCT-vehicles can be up to 20 % more efficient than normal vehicle, due to increased cargo space and uncomminuted energy wood's lower density and fill grade.

When transporting moist chipped energy wood, the normal 25.25-meter vehicle is an economically better option. This is due to the HCT-vehicles lower maximum payload when comparing to the normal vehicle and comminuted energy woods higher fill grade. When transporting dry chipped energy wood, HCT-vehicle's results improve, but break-even comes at longer distances.

All the vehicles struggle to pass the maneuverability test of TrailerWIN. The 30-meter-long HCT-vehicle and the normal 25.25-meter long vehicle can be argued to pass it. However, the 28-meter HCT-vehicle has a steerable bogie on the trailer, which could not be equationed in the software. This truck has passed the test in reality. Steerable bogies may be solution to increase maneuverability also for the other vehicles.

The results are in line previous research. It is possible to reach notable savings when utilizing HCT-vehicles with 76 tonnes of gross weight and with low density cargo transportation. Thus, capitalizing on the increased maximum length in forestry industry is possible in forestry industry. The used methods, especially the cost calculations, can be used by the transport companies to evaluate their potential consequences and savings when introducing HCT-vehicles into their fleet.

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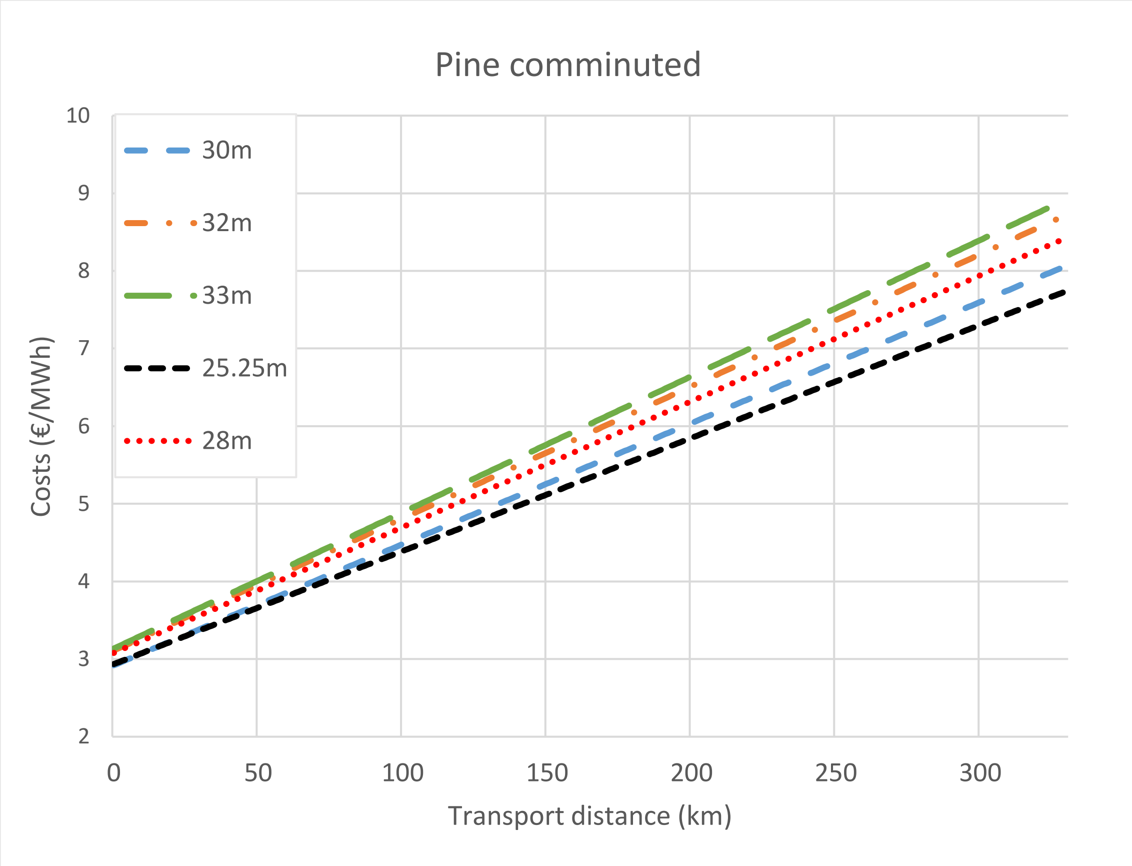
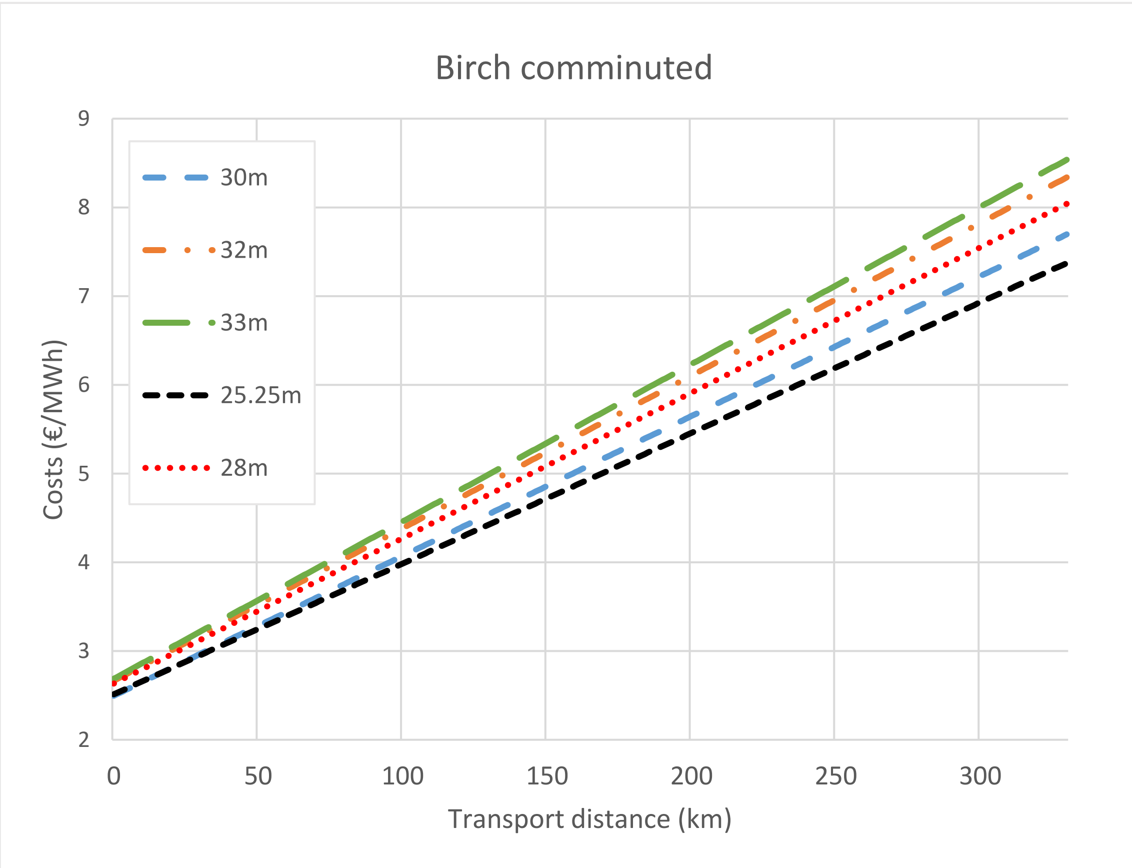
APPENDICES

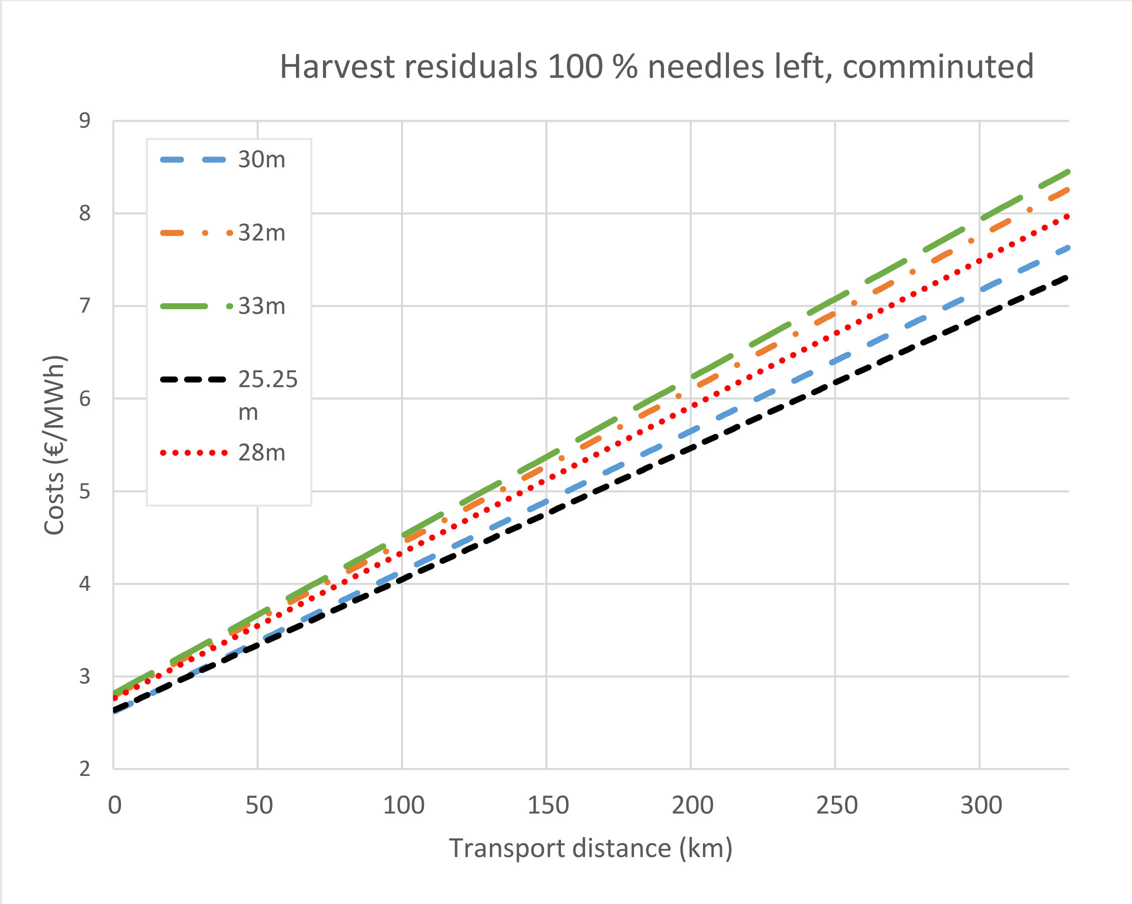
Appendix 1: Usage of cargo and payload weight under the normal scenario

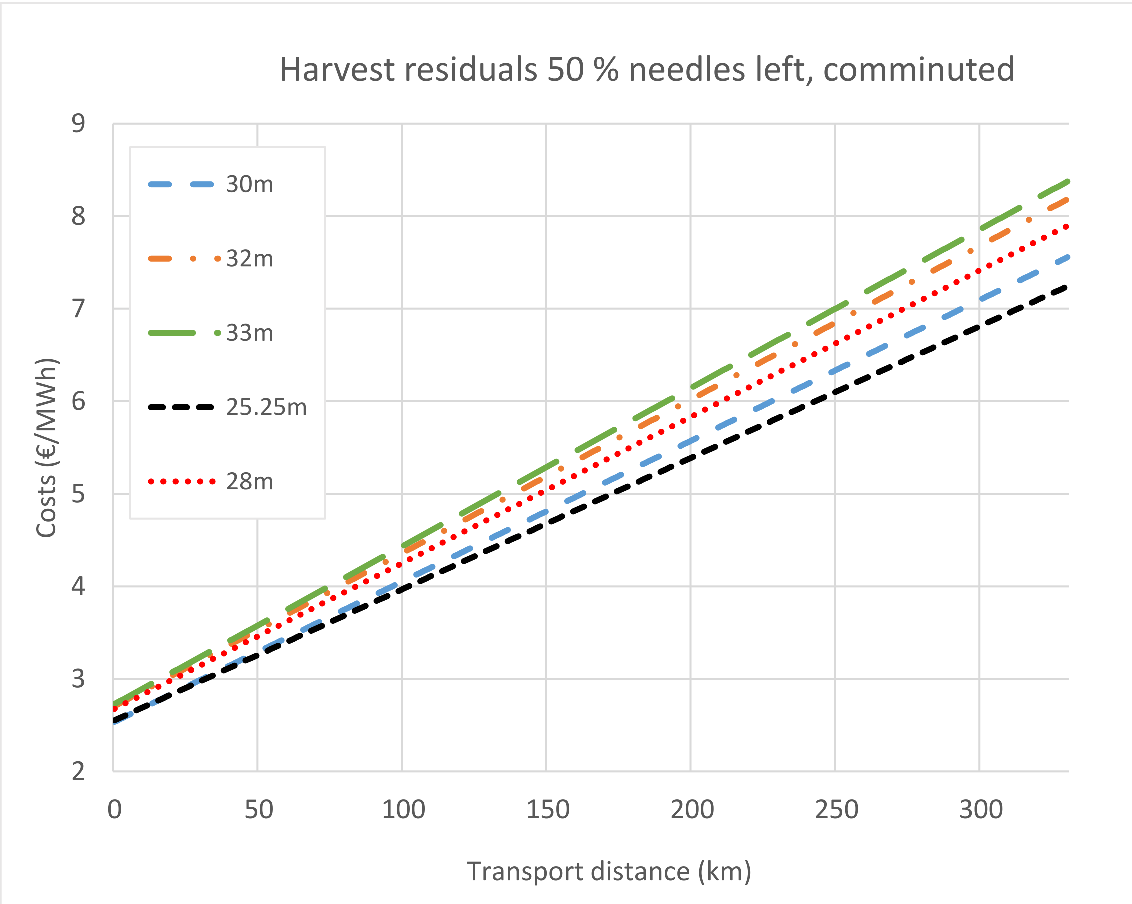
	Energy wood type	30-meter vehicle		32-meter vehivle		33-meter vehicle		25.25-meter vehicle		28-meter vehicle	
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Spruce comminuted	48000,00	150,00	44000,00	137,50	43000,00	134,38	46000,00	143,75	46000,00	143,75
	Spruce uncomminuted	27200,00	170,00	30400,00	190,00	32160,00	201,00	23200,00	145,00	27680,00	173,00
Left	Spruce comminuted	0,0	30,0	0,0	62,5	0,0	76,6	5000,0	11,3	0,0	39,3
	Spruce uncomminuted	17300,0	0,0	10100,0	0,0	7340,0	0,0	19300,0	0,0	14820,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Pine comminuted	48000,00	155,84	44000,00	142,86	43000,00	139,61	46000,00	149,35	46000,00	149,35
	Pine uncomminuted	26180,00	170,00	29260,00	190,00	30954,00	201,00	22330,00	145,00	26642,00	173,00
Left	Pine comminuted	0,0	24,2	0,0	57,1	0,0	71,4	5000,0	5,6	0,0	33,6
	Pine uncomminuted	18320,0	0,0	11240,0	0,0	8546,0	0,0	20170,0	0,0	15858,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Birch comminuted	48000,00	126,32	44000,00	115,79	43000,00	113,16	46000,00	121,05	46000,00	121,05
	Birch uncomminuted	32300,00	170,00	36100,00	190,00	38190,00	201,00	27550,00	145,00	32870,00	173,00
Left	Birch comminuted	0,0	53,7	0,0	84,2	0,0	97,8	5000,0	33,9	0,0	61,9
	Birch uncomminuted	12200,0	0,0	4400,0	0,0	1310,0	0,0	14950,0	0,0	9630,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	est residuals 100% commin	48000,00	141,18	44000,00	129,41	43000,00	126,47	46000,00	135,29	46000,00	135,29
	st residuals 100% uncommi	28900,00	170,00	32300,00	190,00	34170,00	201,00	24650,00	145,00	29410,00	173,00
Left	est residuals 100% commin	0,0	38,8	0,0	70,6	0,0	84,5	5000,0	19,7	0,0	47,7
	st residuals 100% uncommi	15600,0	0,0	8200,0	0,0	5330,0	0,0	17850,0	0,0	13090,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	duals, 50 % of needles left c	48000,00	134,83	44000,00	123,60	43000,00	120,79	46000,00	129,21	46000,00	129,21
	uals, 50 % of needles left ur	30260,00	170,00	33820,00	190,00	35778,00	201,00	25810,00	145,00	30794,00	173,00
Left	est residuals 50% commin	0,0	45,2	0,0	76,4	0,0	90,2	5000,0	25,8	0,0	53,8
	st residuals 50% uncommi	14240,0	0,0	6680,0	0,0	3722,0	0,0	16690,0	0,0	11706,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	duals, 0 % of needles left c	48000,00	129,03	44000,00	118,28	43000,00	115,59	46000,00	123,66	46000,00	123,66
	uals, 0 % of needles left un	31620,00	170,00	35340,00	190,00	37386,00	201,00	26970,00	145,00	32178,00	173,00
Left	vest residuals 0% comminu	0,0	51,0	0,0	81,7	0,0	95,4	5000,0	31,3	0,0	59,3
	est residuals 0% uncommin	12880,0	0,0	5160,0	0,0	2114,0	0,0	15530,0	0,0	10322,0	0,0

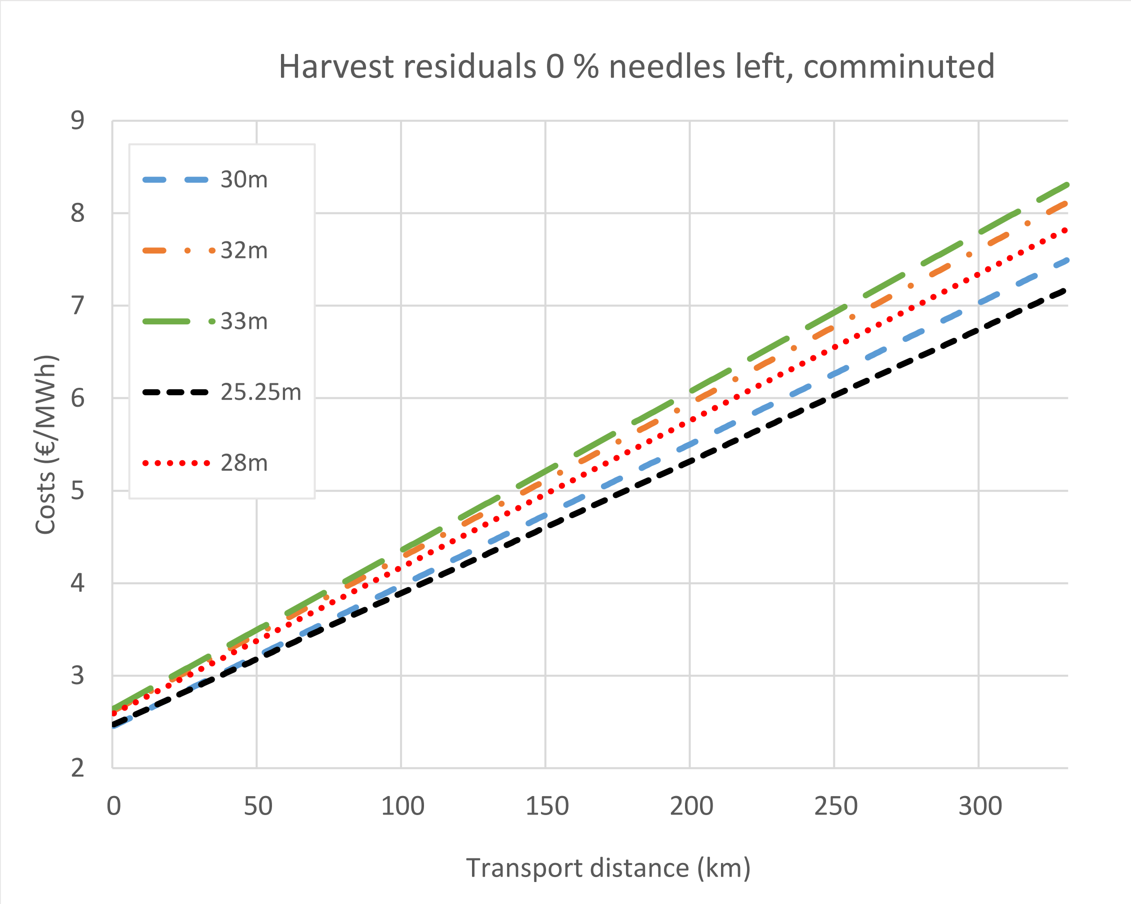
Appendix 2: Absolute and relative costs for different energy wood assortments under the normal scenario

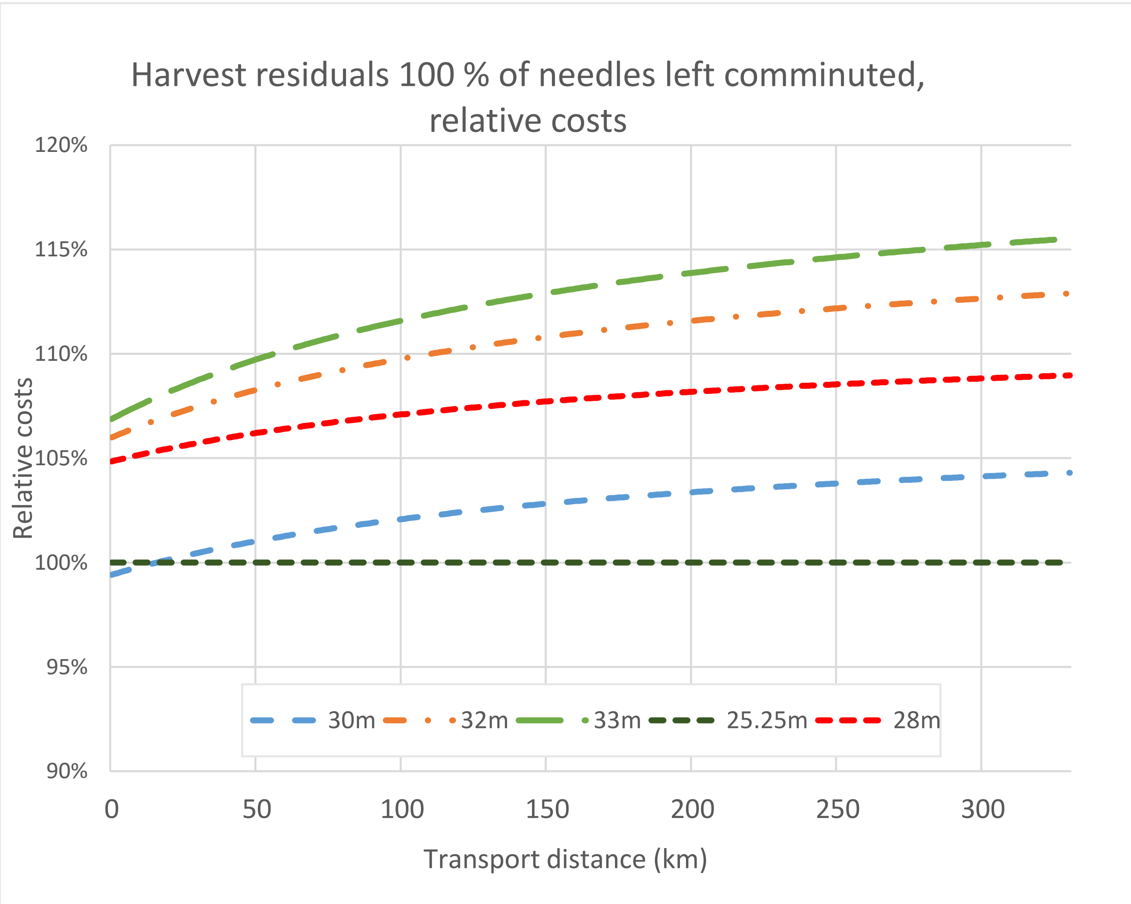


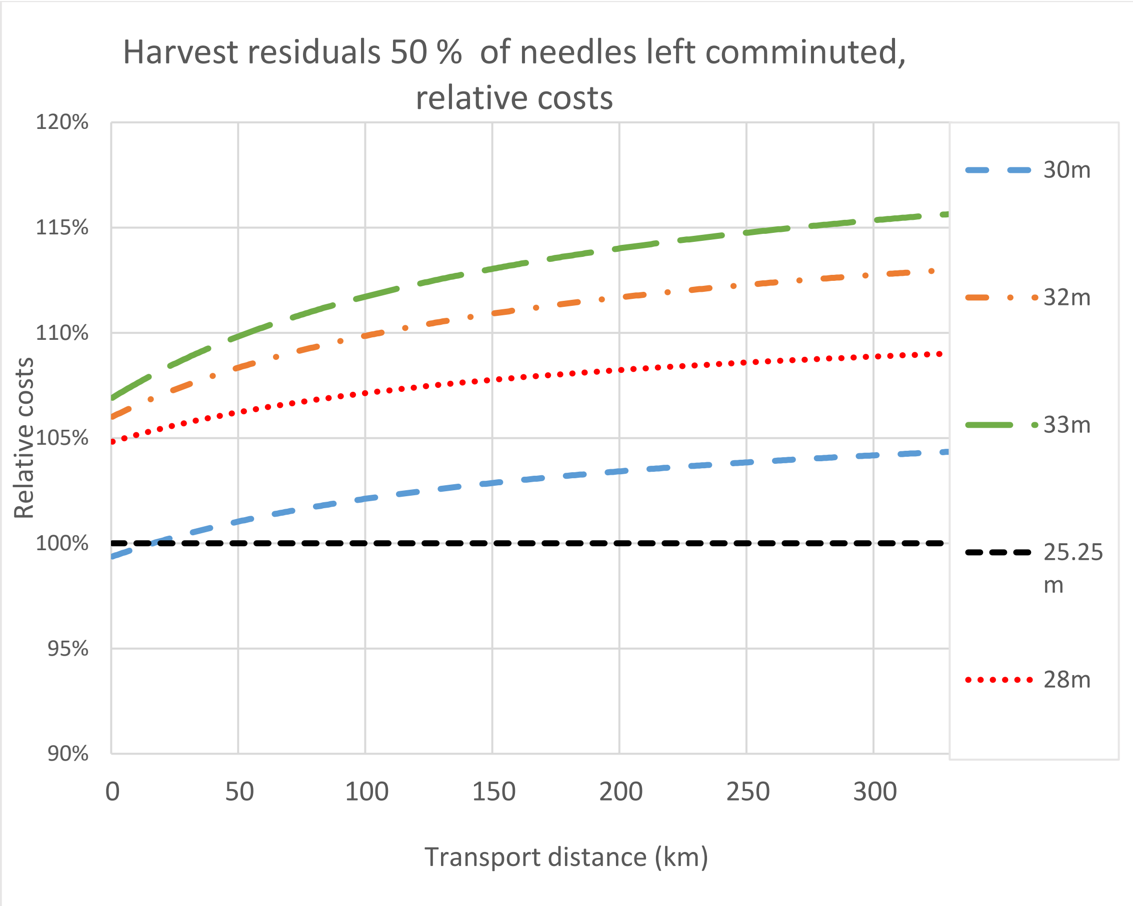


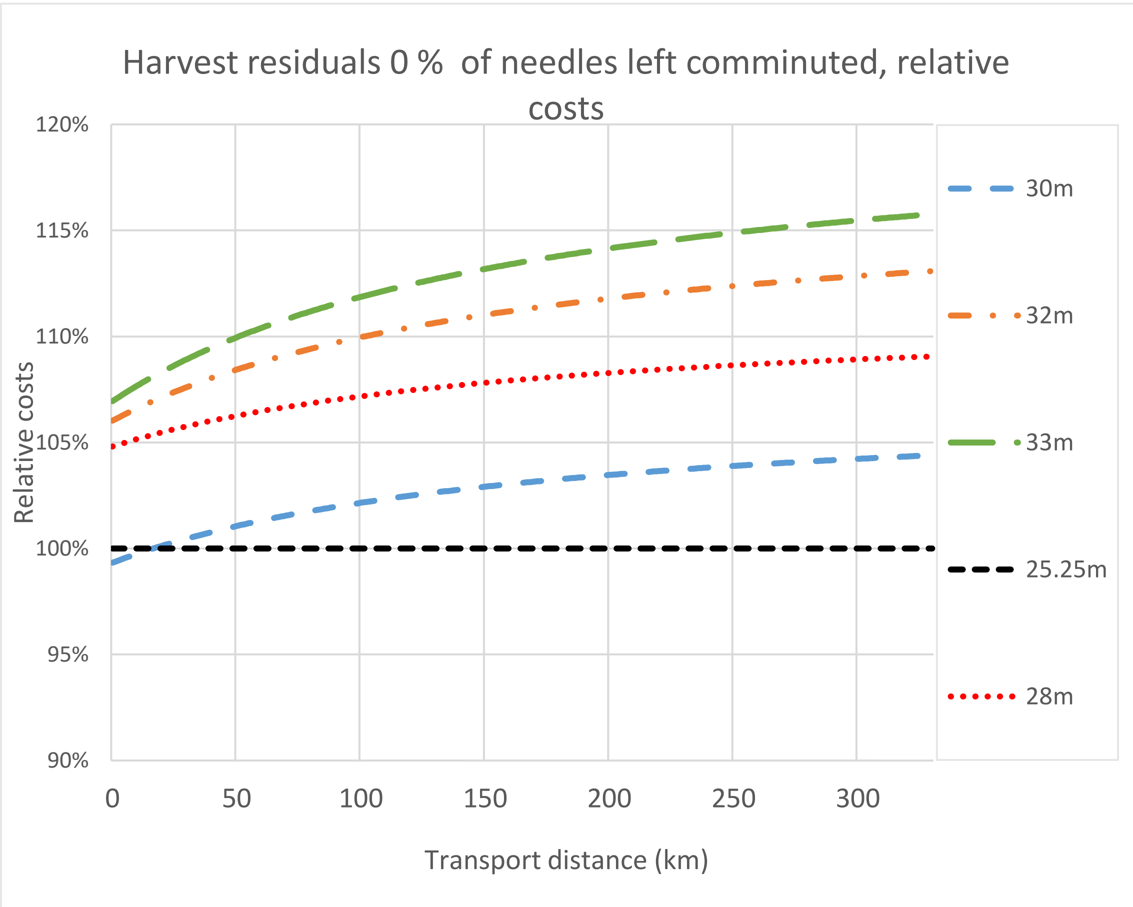

Harvest residuals 100 % needles left, comminuted
Costs (€/MWh)
Transport distance (km)
30m
32m
33m
25.25 m
28m
9
8
7
6
5
4
3
2
0
50
100
150
200
250
300

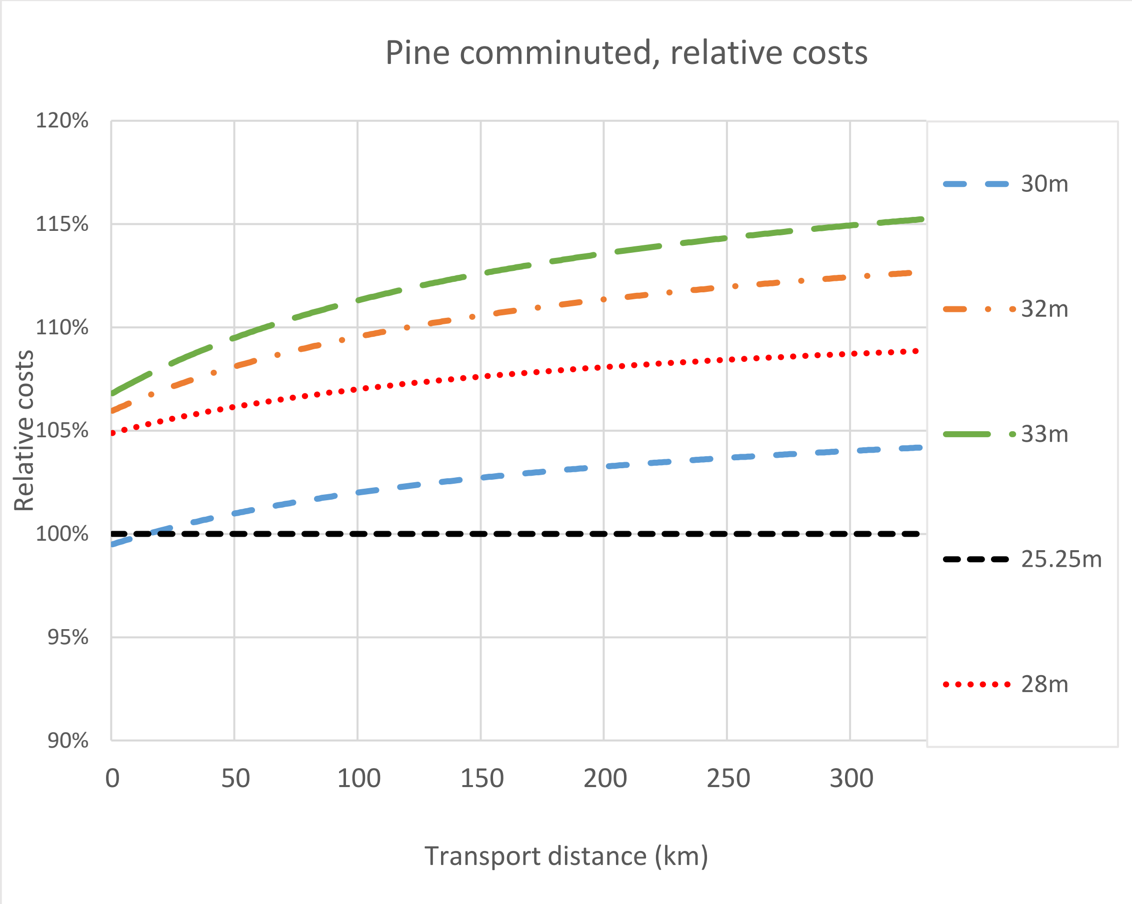

Harvest residuals 50 % needles left, comminuted
Costs (€/MWh)
Transport distance (km)
30m
32m
33m
25.25m
28m
9
8
7
6
5
4
3
2
0
50
100
150
200
250
300


Harvest residuals 0 % needles left, comminuted
Costs (€/MWh)
9
8
7
6
5
4
3
2
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m

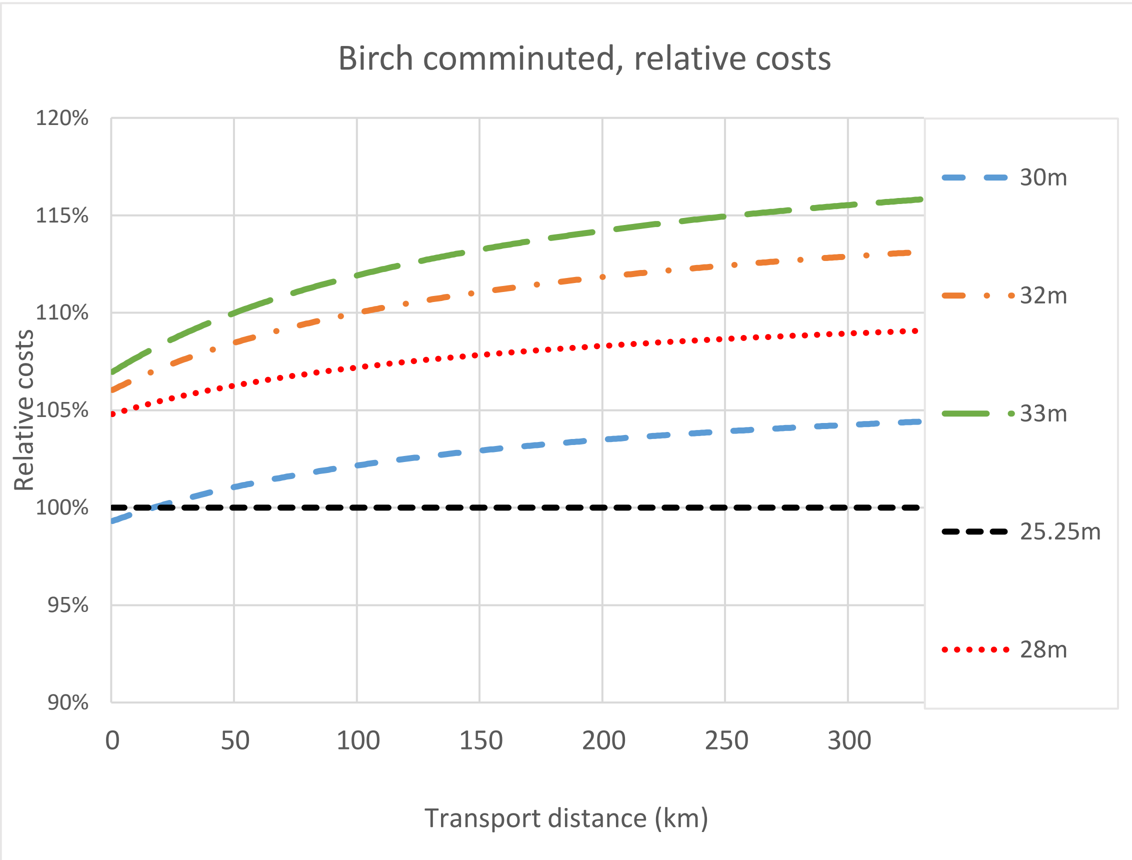

Harvest residuals 100 % of needles left comminuted,
relative costs
Relative costs
120%
115%
110%
105%
100%
95%
90%
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m


Harvest residuals 50 % of needles left comminuted, relative costs
120%
115%
110%
105%
100%
95%
90%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25 m
28m


Harvest residuals 0 % of needles left comminuted, relative costs
120%
115%
110%
105%
100%
95%
90%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m



Pine comminuted, relative costs
120%
115%
110%
105%
100%
95%
90%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m

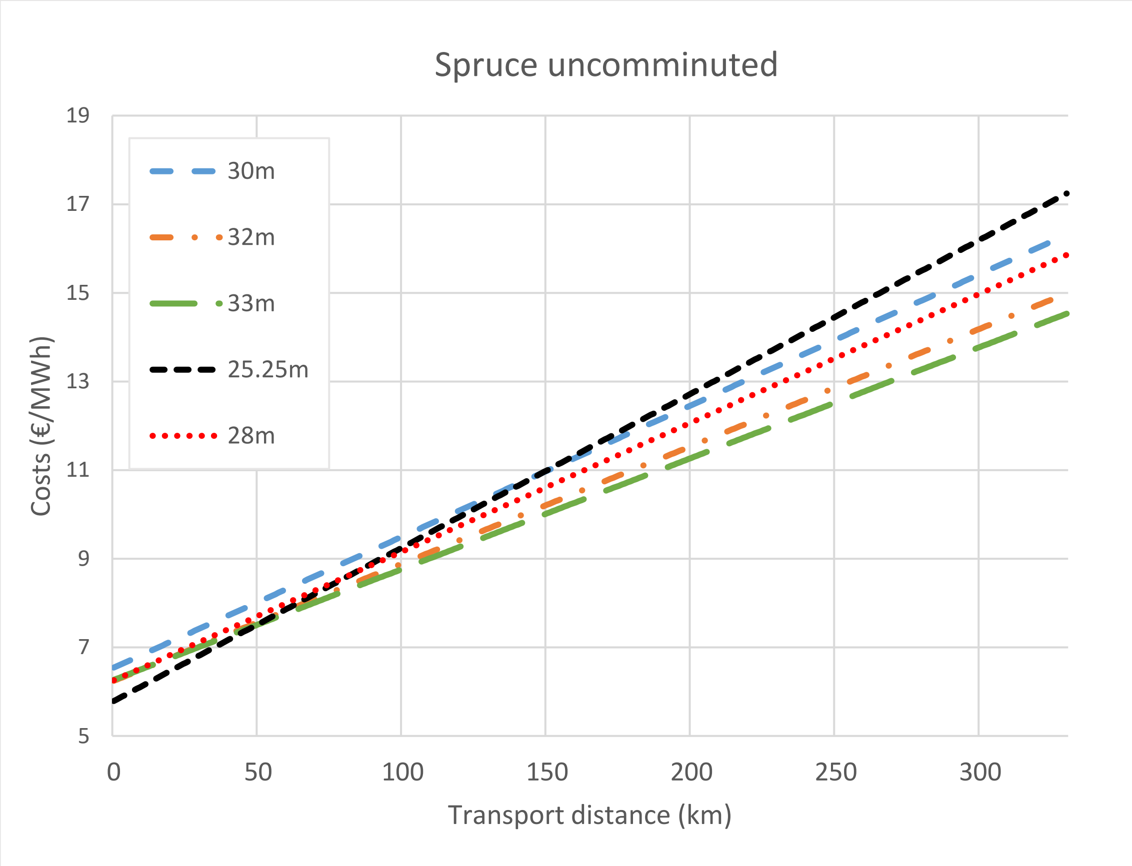


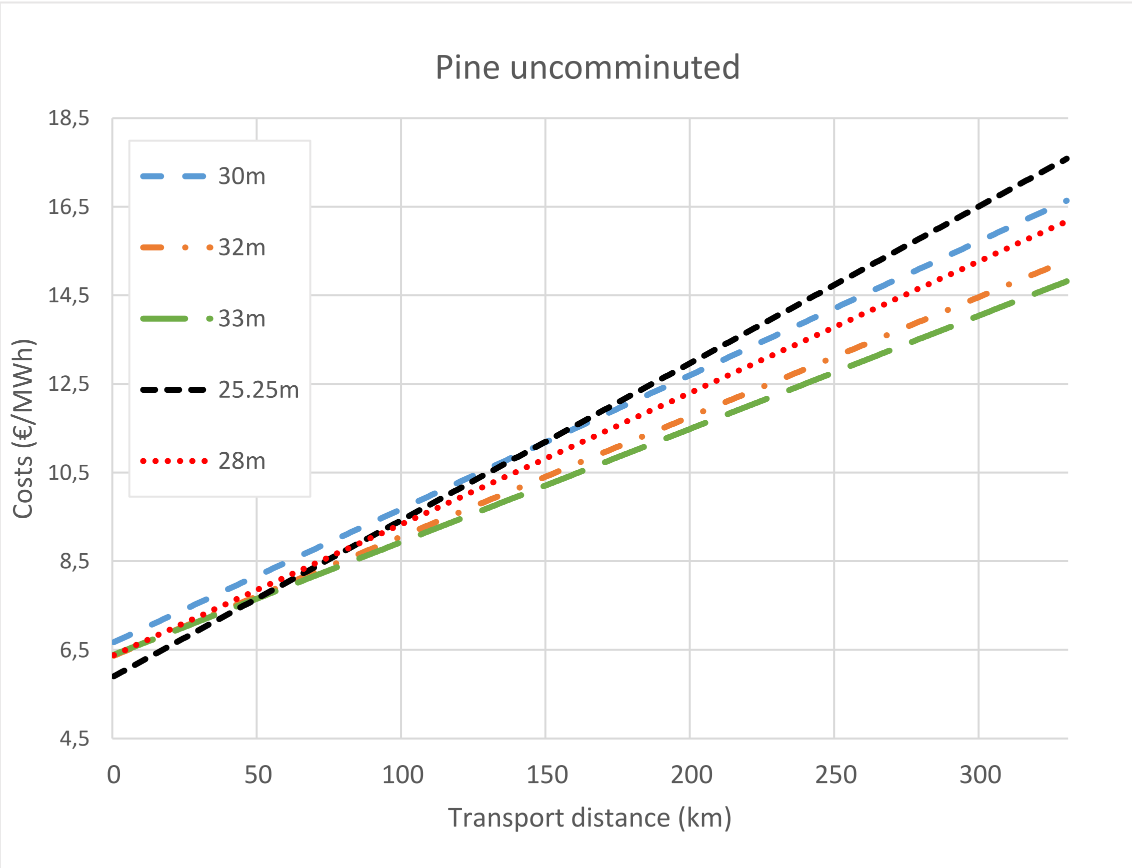
Birch comminuted, relative costs
120%
115%
110%
105%
100%
95%
90%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m

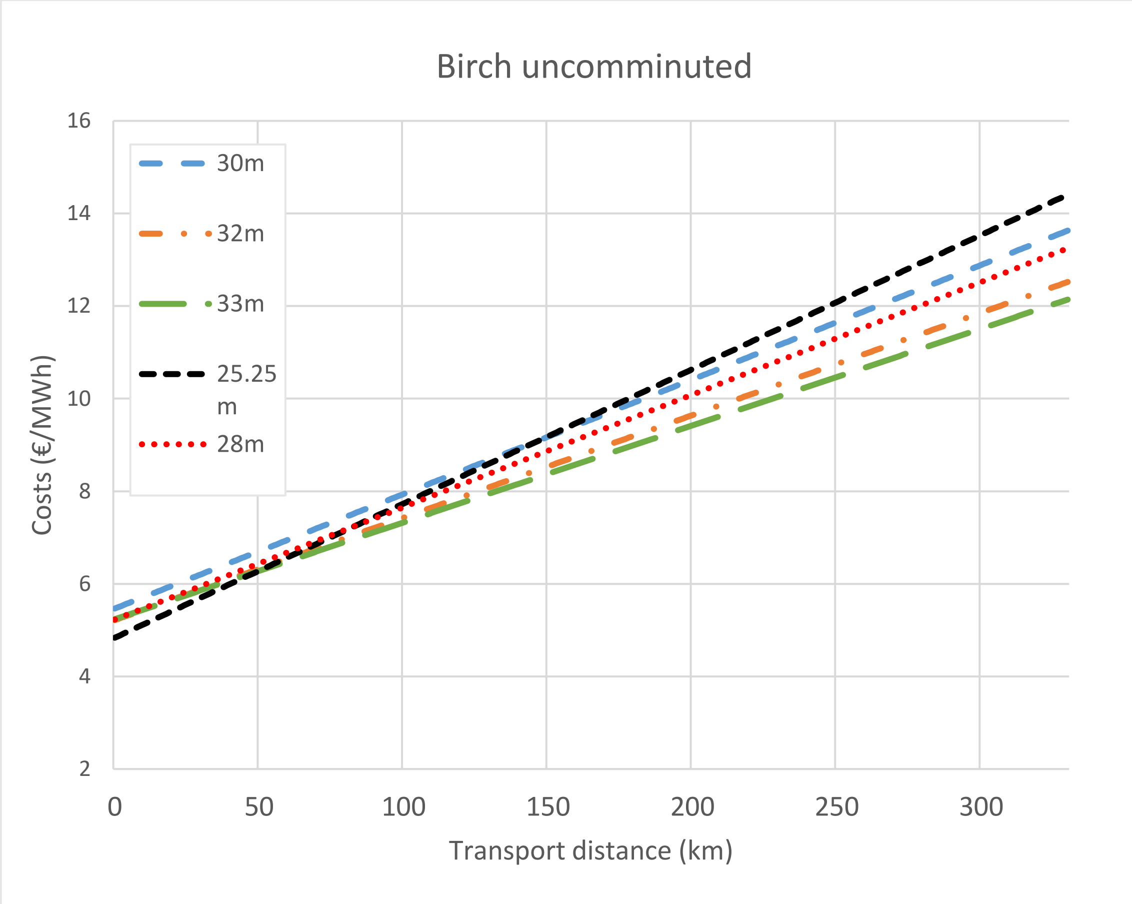
Appendix 3: Usage of cargo and payload weight under the dry scenario

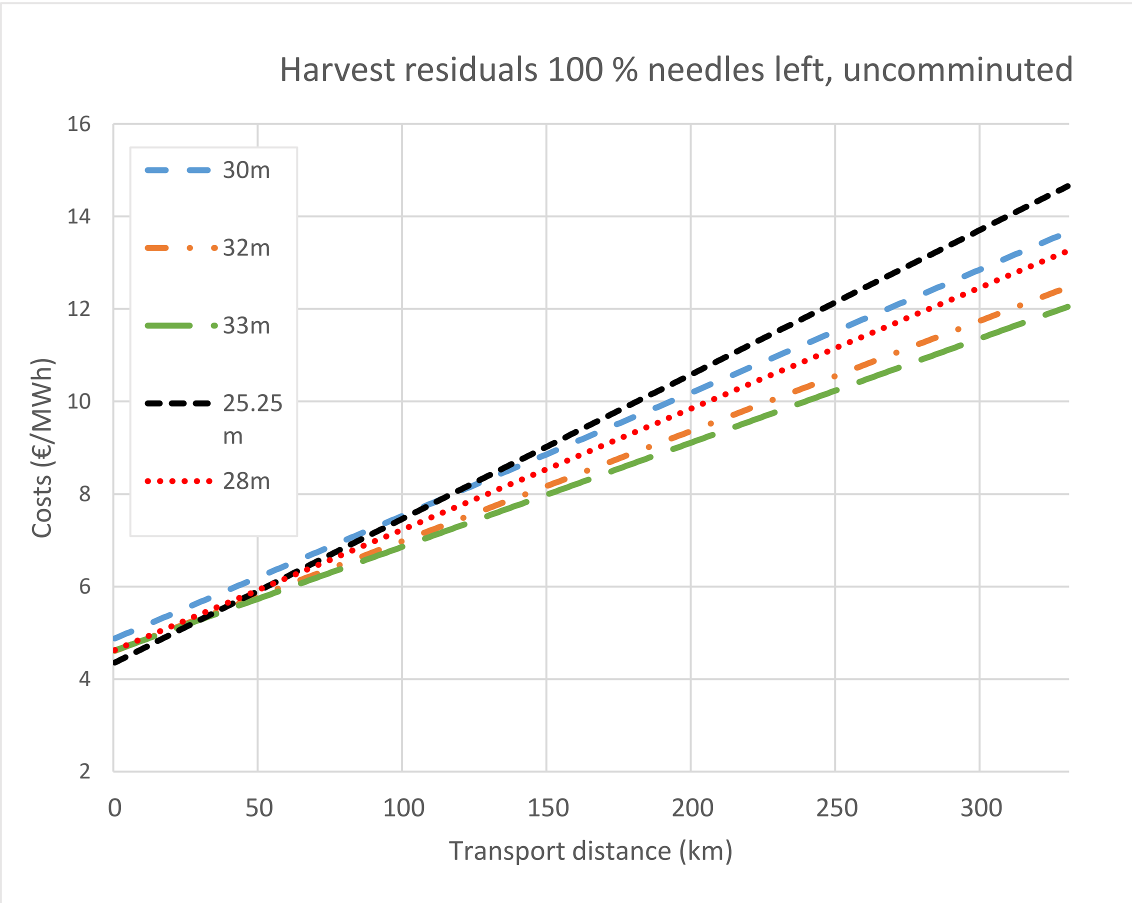
	Energy wood type	30-meter vehicle		32-meter vehicle		33-meter vehicle		25.25-meter vehicle		28-meter vehicle	
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Spruce comminuted	36000,00	180,00	40000,00	200,00	42200,00	211,00	31000,00	155,00	36600,00	183,00
	Spruce uncomminuted	17000,00	170,00	19000,00	190,00	20100,00	201,00	14500,00	145,00	17300,00	173,00
Left	Spruce comminuted	12000,0	0,0	4000,0	0,0	800,0	0,0	20000,0	0,0	9400,0	0,0
	Spruce uncomminuted	27500,0	0,0	21500,0	0,0	19400,0	0,0	28000,0	0,0	25200,0	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Pine comminuted	34650,00	180,00	38500,00	200,00	40617,50	211,00	29837,50	155,00	35227,50	183,00
	Pine uncomminuted	16362,50	170,00	18287,50	190,00	19346,25	201,00	13956,25	145,00	16651,25	173,00
Left	Pine comminuted	13350,0	0,0	5500,0	0,0	2382,5	0,0	21162,5	0,0	10772,5	0,0
	Pine uncomminuted	28137,5	0,0	22212,5	0,0	20153,8	0,0	28543,8	0,0	25848,8	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Birch comminuted	42750,00	180,00	44000,00	185,26	43000,00	181,05	36812,50	155,00	43462,50	183,00
	Birch uncomminuted	20187,50	170,00	22562,50	190,00	23868,75	201,00	17218,75	145,00	20543,75	173,00
Left	Birch comminuted	5250,0	0,0	0,0	14,7	0,0	29,9	14187,5	0,0	2537,5	0,0
	Birch uncomminuted	24312,5	0,0	17937,5	0,0	15631,3	0,0	25281,3	0,0	21956,3	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Harvest residuals, 100 % of needles left comminuted	38250,00	180,00	42500,00	200,00	43000,00	202,35	32937,50	155,00	38887,50	183,00
	Harvest residuals, 100 % of needles left uncomminuted	18062,50	170,00	20187,50	190,00	21356,25	201,00	15406,25	145,00	18381,25	173,00
Left	Harvest residuals 100% comminuted	9750,0	0,0	1500,0	0,0	0,0	8,6	18062,5	0,0	7112,5	0,0
	Harvest residuals 100% uncomminuted	26437,5	0,0	20312,5	0,0	18143,8	0,0	27093,8	0,0	24118,8	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Harvest residuals, 50 % of needles left comminuted	40050,00	180,00	44000,00	197,75	43000,00	193,26	34487,50	155,00	40717,50	183,00
	Harvest residuals, 50 % of needles left uncomminuted	18912,50	170,00	21137,50	190,00	22361,25	201,00	16131,25	145,00	19246,25	173,00
Left	Harvest residuals 50% comminuted	7950,0	0,0	0,0	2,2	0,0	17,7	16512,5	0,0	5282,5	0,0
	Harvest residuals 50% uncomminuted	25587,5	0,0	19362,5	0,0	17138,8	0,0	26368,8	0,0	23253,8	0,0
		weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)	weigth (kg)	Volume (m3)
	Harvest residuals, 0 % of needles left comminuted	41850,00	180,00	44000,00	189,25	43000,00	184,95	36037,50	155,00	42547,50	183,00
	Harvest residuals, 0 % of needles left uncomminuted	19762,50	170,00	22087,50	190,00	23366,25	201,00	16856,25	145,00	20111,25	173,00
Left	Harvest residuals 0% comminuted	6150,0	0,0	0,0	10,8	0,0	26,1	14962,5	0,0	3452,5	0,0
	Harvest residuals 0% uncomminuted	24737,5	0,0	18412,5	0,0	16133,8	0,0	25643,8	0,0	22388,8	0,0

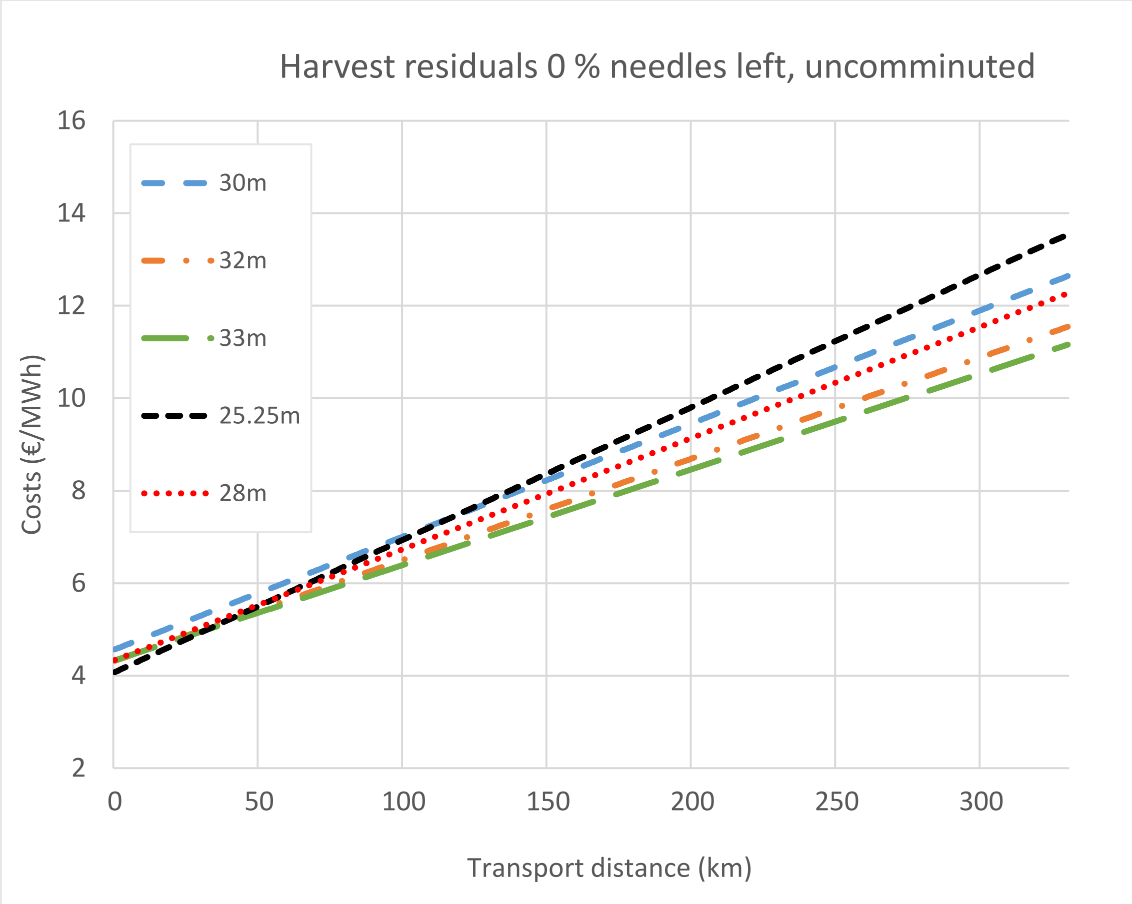
Appendix 4: Absolute and relative costs for different energy wood assortments under the dry scenario

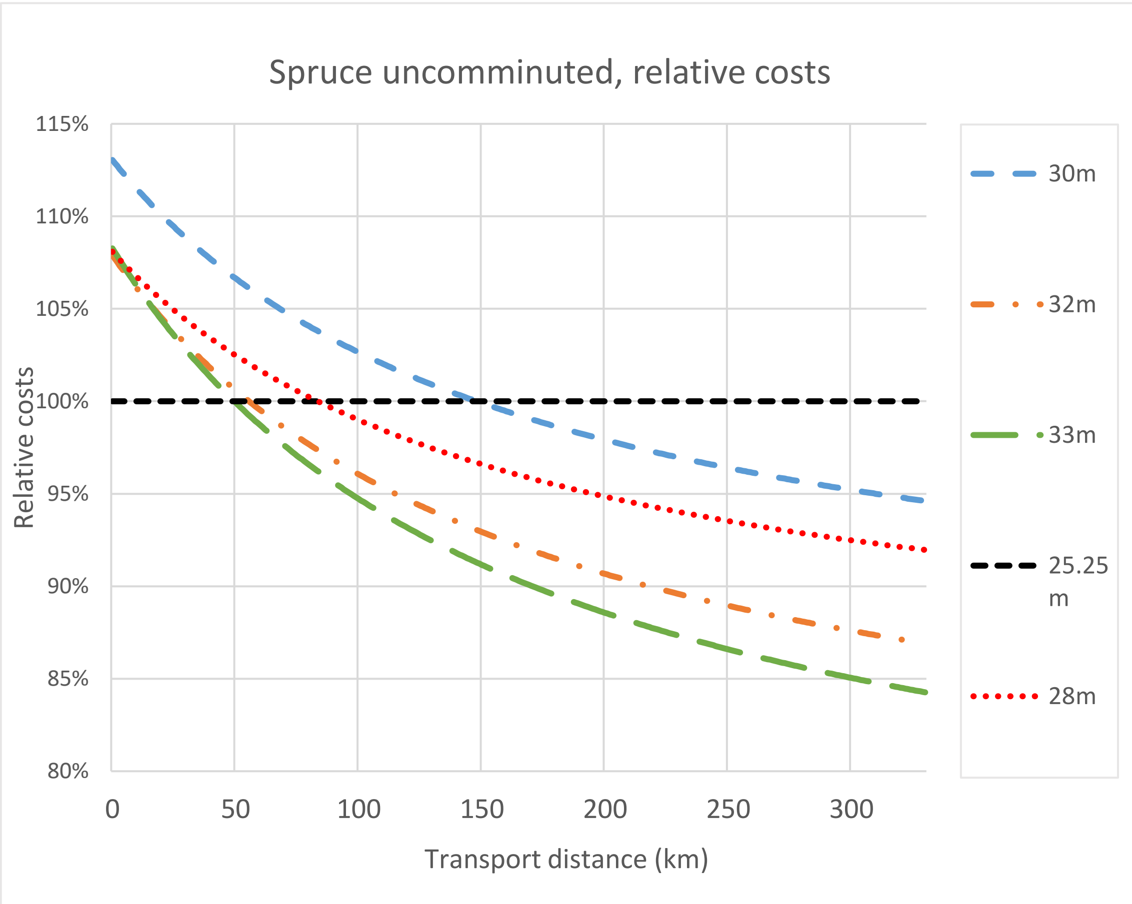


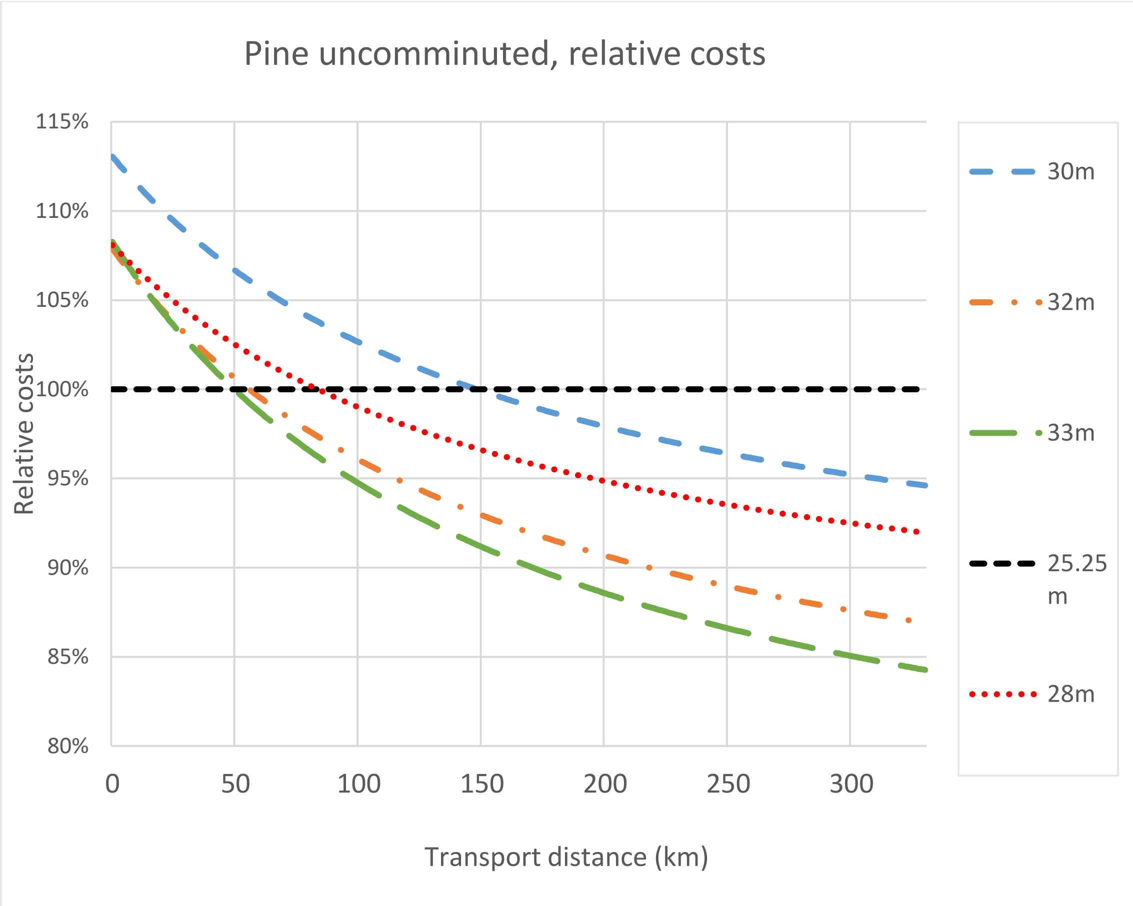


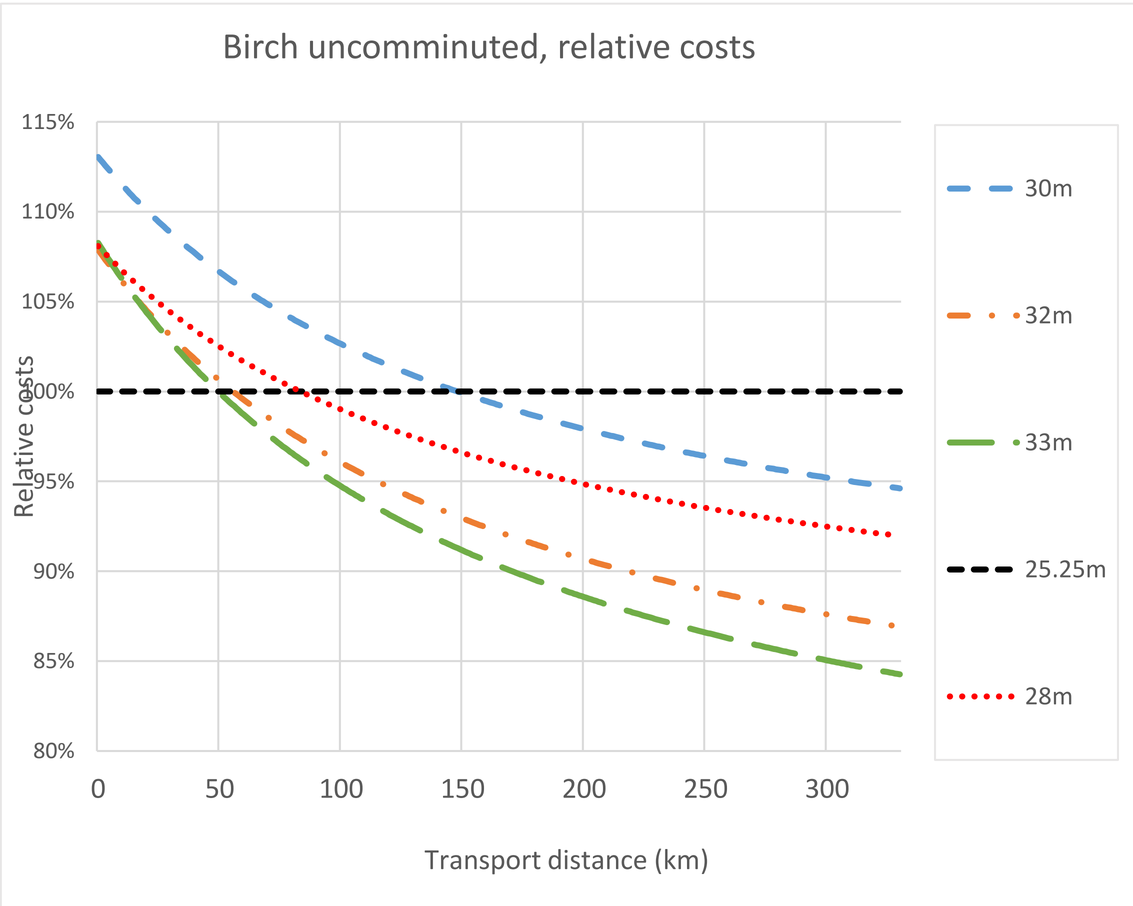

Birch uncomminuted
16
14
12
10
8
6
4
2
0
50
100
150
200
250
300
Costs (€/MWh)
Transport distance (km)
30m
32m
33m
25.25 m
28m

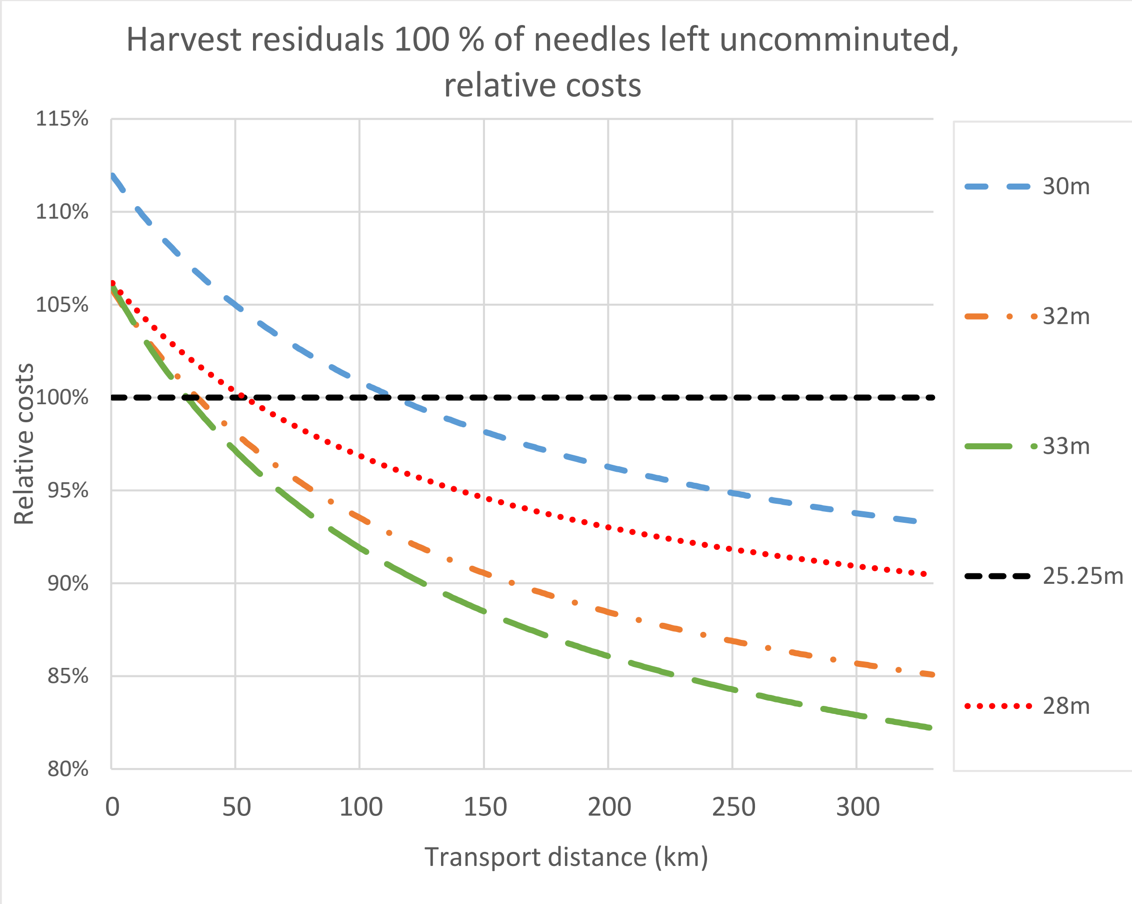

Harvest residuals 100 % needles left, uncomminuted
16
14
12
10
8
6
4
2
0
50
100
150
200
250
300
Costs (€/MWh)
Transport distance (km)
30m
32m
33m
25.25 m
28m

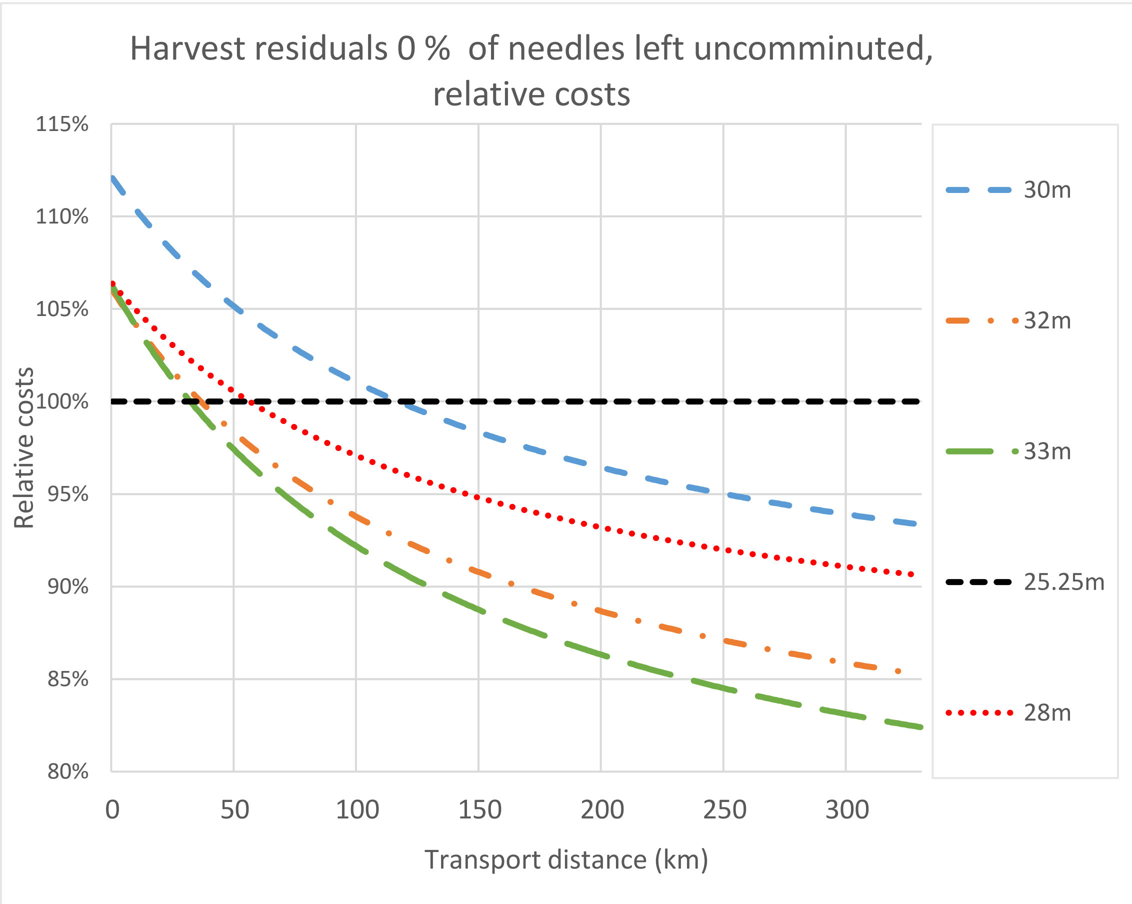

Harvest residuals 0 % needles left, uncomminuted
Costs (€/MWh)
16
14
12
10
8
6
4
2
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m


Spruce uncomminuted, relative costs
Relative costs
115%
110%
105%
100%
95%
90%
85%
80%
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25 m
28m


Pine uncomminuted, relative costs
115%
110%
105%
100%
95%
90%
85%
80%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25 m
28m


Birch uncomminuted, relative costs
115%
110%
105%
100%
95%
90%
85%
80%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m


Harvest residuals 100 % of needles left uncomminuted, relative costs
115%
110%
105%
100%
95%
90%
85%
80%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m


Harvest residuals 0 % of needles left uncomminuted, relative costs
115%
110%
105%
100%
95%
90%
85%
80%
Relative costs
0
50
100
150
200
250
300
Transport distance (km)
30m
32m
33m
25.25m
28m